

Vortex distribution and interaction within a perturbed turbulent boundary layer

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ABSTRACT

The downstream evolution of coherent vortices generated by cylinders mounted parallel to and above a bounding surface within a turbulent boundary layer was investigated using planar particle image velocimetry (PIV). Experiments were conducted in a recirculating water channel at $Re_\tau = 1470$, with cylinder diameters of $D/\delta = 0.045$ and 0.09 and gap heights ranging from $G/\delta = 0.045$ to 0.18 . Individual vortices were identified using Q -criterion and minimum area thresholds, enabling quantification of vortex count, circulation, and spatial distribution. In all cases considered, the total number of identified vortices increases strongly downstream of the cylinder and remains above unperturbed levels to the limit of the field of view 2.5δ downstream of the cylinder. Negative (clockwise) vortices consistently outnumber positive (counterclockwise) vortices, reflecting the mean clockwise shear imposed by the wall. The magnitude of the disturbance in mean velocity, turbulent intensity, and number of identified vortices increases with both G/δ and D/δ . In all cases, the wake disturbance extends further from the wall with increasing downstream distance. Comparison between v_{rms} and vortex count profiles shows good correspondence, supporting the interpretation that vortices are key contributors to wall-normal motions.

1. Introduction

Discrete objects immersed within a turbulent boundary layer disturb the existing turbulent eddies and their organization. In environmental flows, the characteristics, evolution, and downstream persistence of the disturbance can affect sediment and nutrient transport as well as the underlying shear stress on a seafloor or riverbed.

In the current work, we consider flow downstream of a cylinder in crossflow mounted parallel to and above the bounding surface. Key parameters of interest include D/δ and G/δ , where D represents the cylinder diameter, G is the gap between the cylinder bottom and the wall, and δ is the boundary layer thickness. Also considered are the friction Reynolds number (Re_τ) and the Strouhal number (St) associated with bluff body wakes. The friction Reynolds number is defined

as the friction velocity u_τ times the boundary layer thickness, divided by the kinematic viscosity of the fluid, ν . The Strouhal number represents a shedding frequency multiplied by a characteristic length scale divided by the oncoming flow velocity.

A number of previous studies, e.g. Bearman & Zdravkovich (1978), Zhou et al. (2021), and Wang & Tan (2008), considered relatively large cylinder diameters ($D/\delta > 1$) and examined the influence of G/D on the Strouhal number associated with cylinder vortex shedding and on the nature of the shedding itself. More recently, Torres De Jesús et al. (2024) investigated disturbances behind a smaller cylinder ($D/\delta = 0.05$) positioned at different gap heights in the outer region of a turbulent boundary layer. The authors found evidence of large-scale structure suppression and augmentation of small-scale energy at and below the cylinder height.

To complement previous investigations, the current study aims to understand the effects of flow downstream of relatively small cylinders ($D/\delta \sim 0.1$) embedded in the logarithmic region of a boundary layer, where unperturbed turbulence levels are high and the oncoming flow includes coherent structures spanning a range of length scales. Both D/δ and G/δ are varied to investigate wake-induced perturbations and how they interact with the typical eddies and structures in the unperturbed flow.

2. Methodology

Experiments were performed in a recirculating water channel located in the Turbulent Shear Flow Laboratory in the Aerospace Engineering and Mechanics Department at the University of Minnesota. The channel test section dimensions are $7.80 \times 1.12 \times 0.58$ m. Cylinders were mounted magnetically on the bottom wall a distance 4.2 m downstream of a tripwire located at the test section entrance, as shown in Figure 1. The unperturbed flow speed ($U_\infty = 0.494$ m/s) and conditions ($Re_\tau = 1470$ at the cylinder location) replicate those of previous work completed in the same water channel (Tee, 2021). Under these conditions, the boundary layer thickness at the streamwise location of the cylinder is $\delta = 69$ mm. In addition to the unperturbed condition, flow measurements were performed with D/δ of 0.045 and 0.09 and G/δ of 0.045, 0.09, and 0.18. The corresponding cylinder diameters were 6.35 mm (135 viscous units) and 3.175 mm (67 viscous units), and gap widths were 12.7 mm (270 viscous units), 6.35 mm (135 viscous units), and 3.175 mm (67 viscous units).

Unperturbed flow and flow downstream of each cylinder/gap combination were characterized using planar particle image velocimetry (PIV). For PIV imaging, the flow was seeded with $13 \mu\text{m}$ silver-coated hollow glass spheres (Potters Industries LLC), $\rho = 1600 \text{ kg m}^{-3}$. Streamwise/wall-normal image planes were illuminated by two New Wave Solo II Nd:YAG 532 nm lasers controlled by a TSI 610034 synchronizer box. Image pairs were captured with three TSI PowerView Plus 4MPE Cameras (16-bit CCD), positioned as shown in Figure 1. Cameras 1 and 2 were aligned to

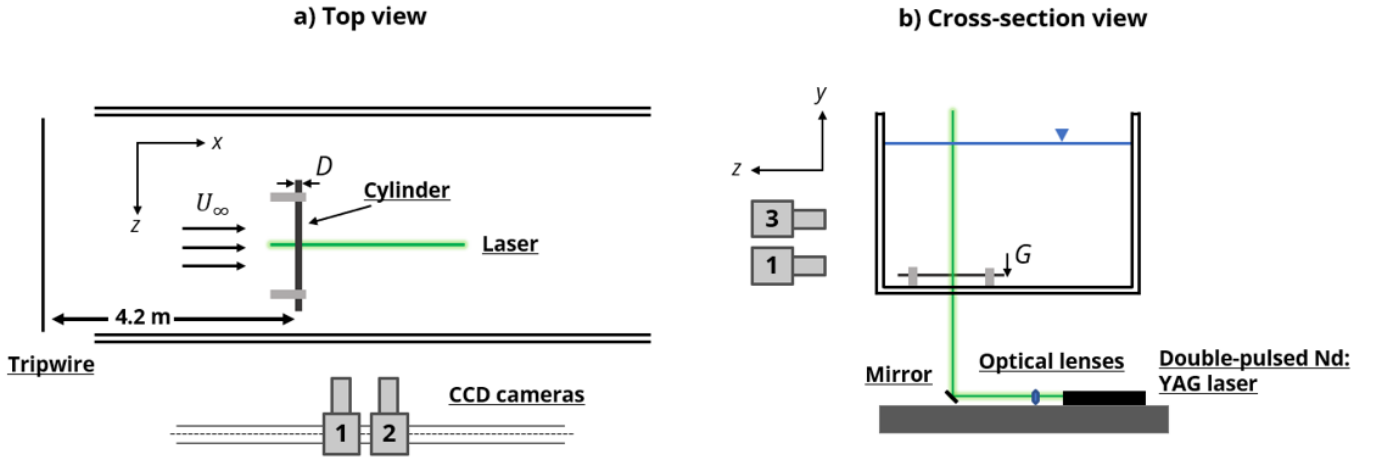


Figure 1. Experimental setup. (a) Top view: cylinder and laser sheet position relative to tripwire. (b) Cross-section view: laser path through mirror and sheet optics. Camera positions are indicated for Cameras 1, 2, and 3.

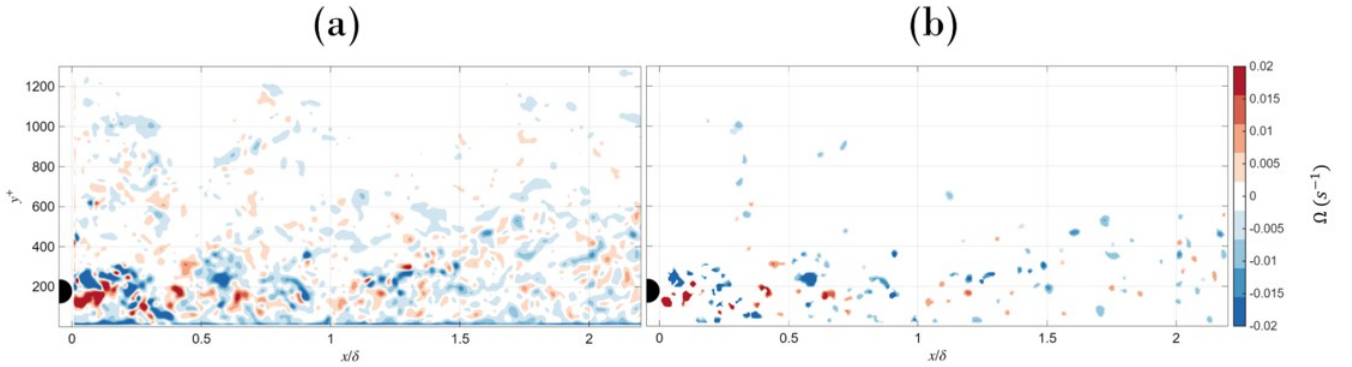


Figure 2. (a) Instantaneous vorticity field for $D/\delta = 0.09$, $G/\delta = 0.09$. (b) Identified vortices based on Q -criterion threshold of $0.0003s^{-2}$ and minimum area of 5 grid points.

provide a relatively long field of view in the streamwise (x) direction while Camera 3 was positioned to monitor the outer edge of the boundary layer. Each camera was equipped with a Nikon AF Micro-Nikkor 105mm lens set at $f/2.8$. The acquisition rate was set at 1 Hz to guarantee statistical independence between fields. A total of 2100 image pairs was captured for each flow condition. Image magnification was 0.045 mm per pixel.

The PIV pre-processing included masking of the raw images and background subtraction to remove wall reflections and enhance contrast. The size of the resulting field of view from Cameras 1 and 2 was 2.5δ in the streamwise direction and 1.2δ in the wall normal direction. Vector fields were computed using DaVis 10.2 from LaVision with a final interrogation window size of 32 by 32 pixels and an overlap of 75%. With this configuration the vector spacing was approximately 7.5 viscous units. The quarter area rule was used to determine the time between laser pulses (Δt). For an 8 pixel displacement (25% of 32), $\Delta t = 1200 \mu s$ was selected.

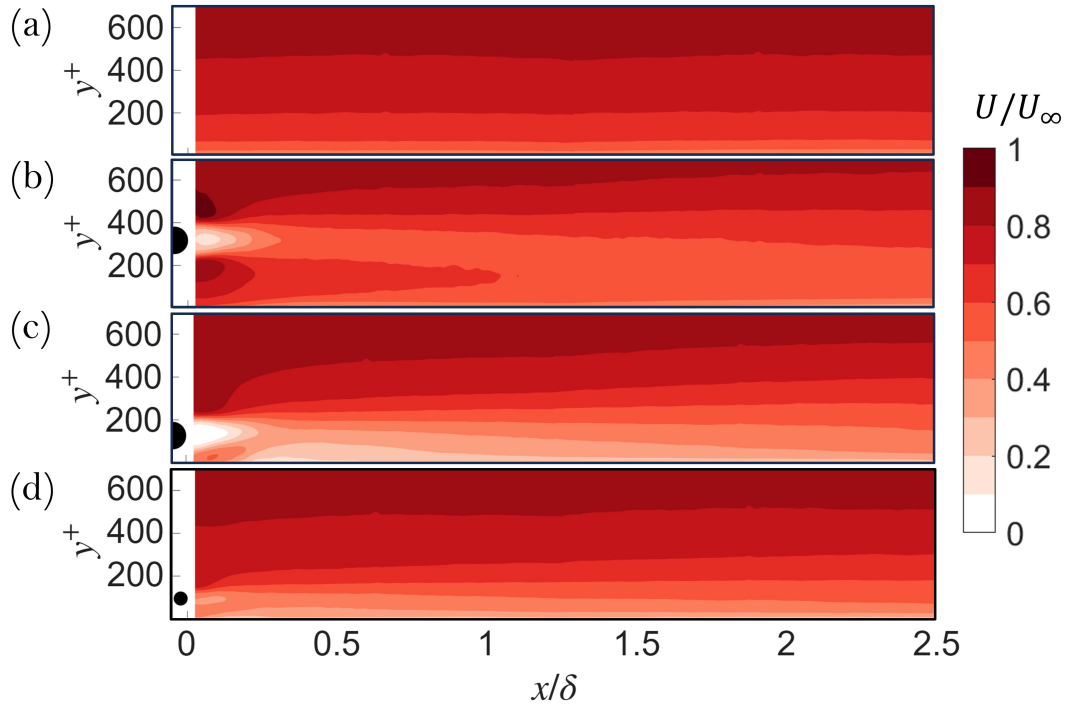


Figure 3. Contours of mean streamwise velocity $\bar{U}/U_\infty$ for (a) unperturbed boundary layer, (b) $D/\delta = 0.09$, $G/\delta = 0.18$; (c) $D/\delta = 0.09$, $G/\delta = 0.045$; and (d) $D/\delta = 0.045$, $G/\delta = 0.045$.

Individual vortices were identified using a signed Q -criterion, and their properties (area, vorticity, centroid position, and circulation) were extracted, as shown in Figure 2. A minimum Q threshold was selected ($Q_{crit} > 0.0003 \text{ s}^{-2}$) to delineate coherent vortex core regions. This specific threshold value was chosen as relatively insensitive to minor variations in the total number of vortices detected. Additionally, a minimum core area filter of 5 connected grid points was applied.

Vortices identified in a given data set were binned along the streamwise and wall-normal directions, separating positive and negative signed contributions for analysis. After screening to check the sensitivity, a bin height of approximately 40 viscous units (wall-normal direction) and bin width of 100 viscous units (streamwise direction) was selected in order to generate wall-normal profiles of vortex number and circulation variation at different locations downstream from the cylinder.

3. Results

3.1. Mean Streamwise Velocity

The modification of the mean streamwise velocity by each cylinder is presented in Figure 3. The introduction of the cylinder induces a local flow acceleration both above and below the obstacle,

accompanied by a pronounced velocity deficit in its immediate wake. The disturbance to the mean velocity field persists far downstream, at least 2.5δ , with discernible differences from unperturbed flow for all cylinder cases.

For the large cylinder ($D/\delta = 0.09$) with large gap ($G/\delta = 0.18$), the flow acceleration above and below the obstacle persists about 0.2δ downstream of the cylinder. In contrast, the large cylinder with small gap ($G/\delta = 0.045$) exhibits a clear acceleration above the cylinder that extends until 0.2δ , while in the gap between the wall and the cylinder a short local velocity increase is quickly followed by notably lower values as the flow expands downstream of the cylinder and possibly separates from the wall. The profiles for the small cylinder ($D/\delta = 0.045$) with small gap ($G/\delta = 0.045$) produce less intense mean flow distortion; however, the mean wake does not return to the unperturbed profile within the limit of the measurement domain ($x = 2.5\delta$).

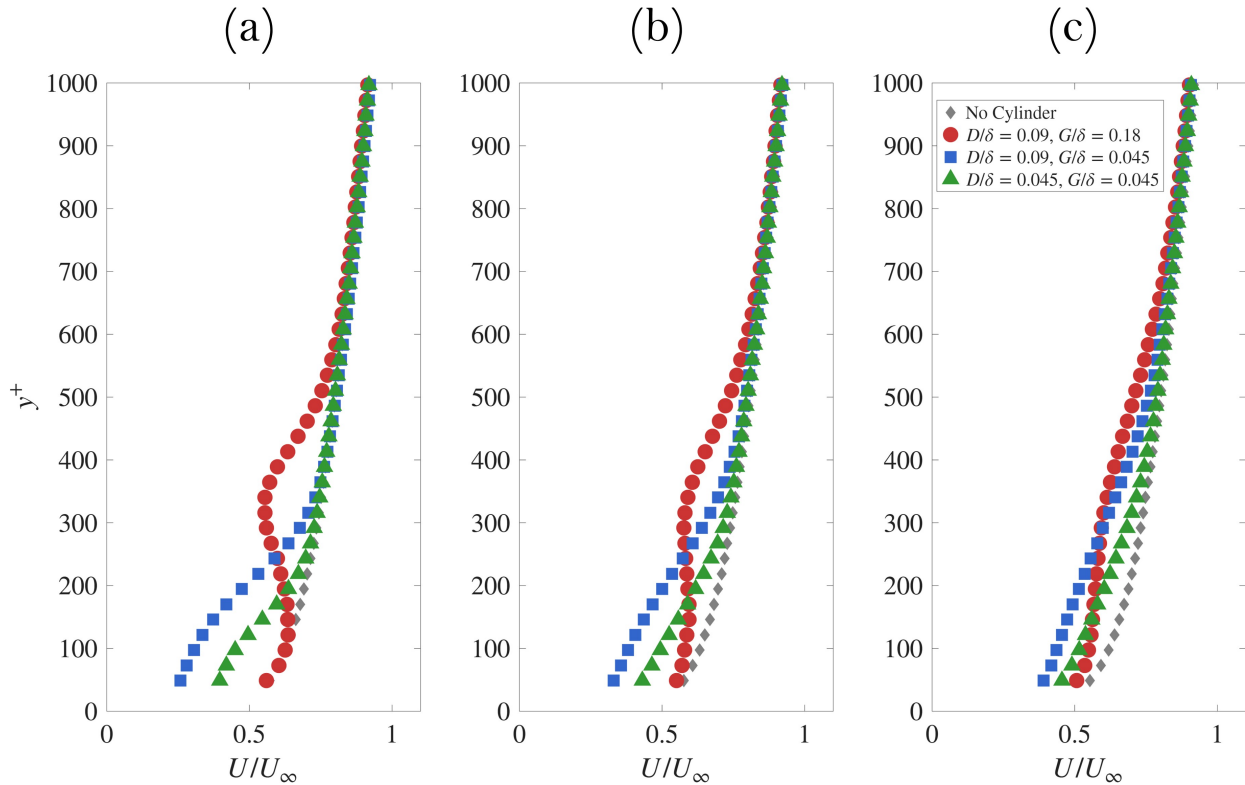


Figure 4. Wall-normal profiles of mean streamwise velocity $\bar{U}/U_\infty$ at (a) $x/\delta = 0.5$; (b) 1.2; and (c) 2.2 comparing the effects of unperturbed, $D/\delta = 0.09$ at $G/\delta = 0.18$ (red), $D/\delta = 0.09$ at $G/\delta = 0.045$ (blue), and $D/\delta = 0.045$ at $G/\delta = 0.045$ (green).

This is more apparent in the streamwise velocity profiles at $x/\delta = 0.5$; 1.2; and 2.2, as shown in Figure 4. In these figures, the baseline unperturbed profiles are shown as small gray diamonds. All cylinder case curves (blue, green red) stay fully to the left of the gray baseline. Thus, already at $x/\delta = 0.5$, there is no acceleration above or below the cylinder. For the large cylinder with large gap (red circles), the decelerated wake region is initially contained between $100 < y^+ < 550$,

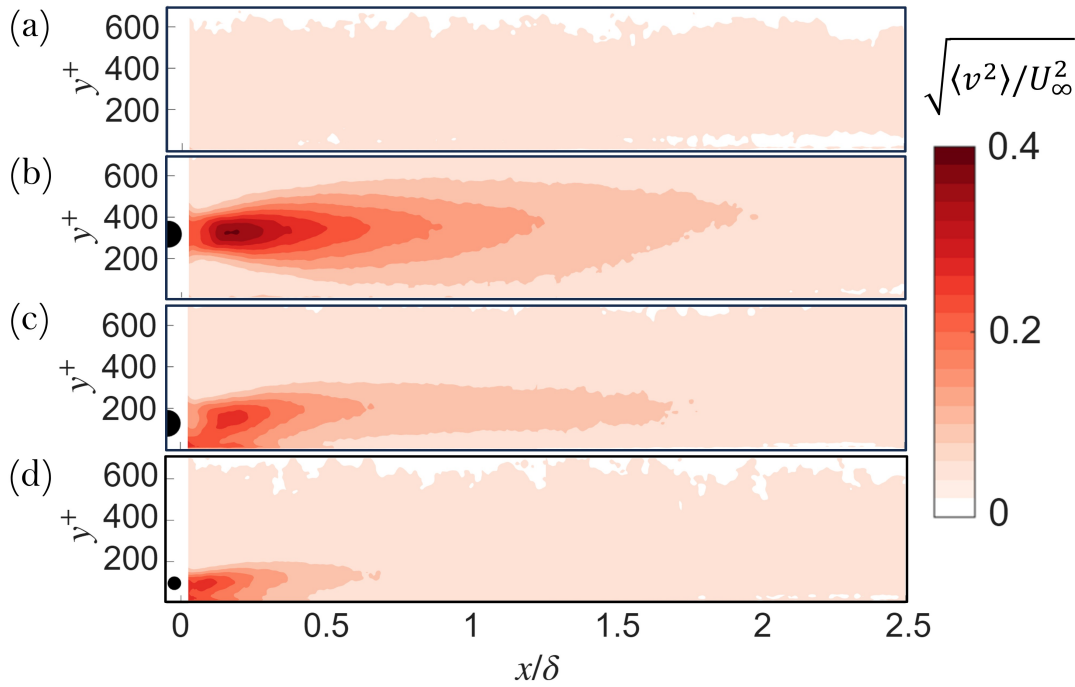


Figure 5. Contours of wall-normal turbulent intensity $\sqrt{\langle v^2 \rangle / U_\infty^2}$ for (a) Unperturbed, (b) $D/\delta = 0.09$, $G/\delta = 0.18$, (c) $D/\delta = 0.09$, $G/\delta = 0.045$, and (d) $D/\delta = 0.045$, $G/\delta = 0.045$.

above and below which the mean velocity is similar to the unperturbed case. The lowest value in the wake region is located at $y^+ = 340$, approximately the same height as the cylinder center ($y^+ = 337$). For this cylinder and gap, the wake region broadens downstream to $50 < y^+ < 600$ at $x/\delta = 1.2$, and approximately $50 < y^+ < 700$ at $x/\delta = 2.2$.

For the large cylinder with small gap (blue squares), the lowest mean velocities occur at the measurement point closest to the wall. At $x/\delta = 0.5$ and $y^+ = 50$, the mean velocity reaches only $0.25U_\infty$, much lower than in the unperturbed flow and the large-cylinder high-gap case that have values of $0.55U_\infty$ at the same wall-normal location. The profiles for the smaller cylinder with small gap ($D/\delta = 0.045$, $G/\delta = 0.045$, green triangles) resemble those for the larger cylinder with matched gap although the momentum deficits are weaker. Nevertheless, the effect of the disturbance persists, and a complete return to equilibrium has not yet been achieved by $x/\delta = 2.2$.

3.2. Wall-Normal Turbulence Intensity

The influence of the cylinder on the turbulent fluctuations is next considered through the wall-normal turbulence intensity, v_{rms} . Figure 5 presents the v_{rms} fields for the unperturbed case, the large cylinder ($D/\delta = 0.09$) at two gap heights, and the small cylinder ($D/\delta = 0.045$) at the low gap height. For the large cylinder with large gap ($G/\delta = 0.18$, Figure 5(b)), the cylinder generates a strong and spatially broad increase in v_{rms} within the wake region, indicating significantly en-

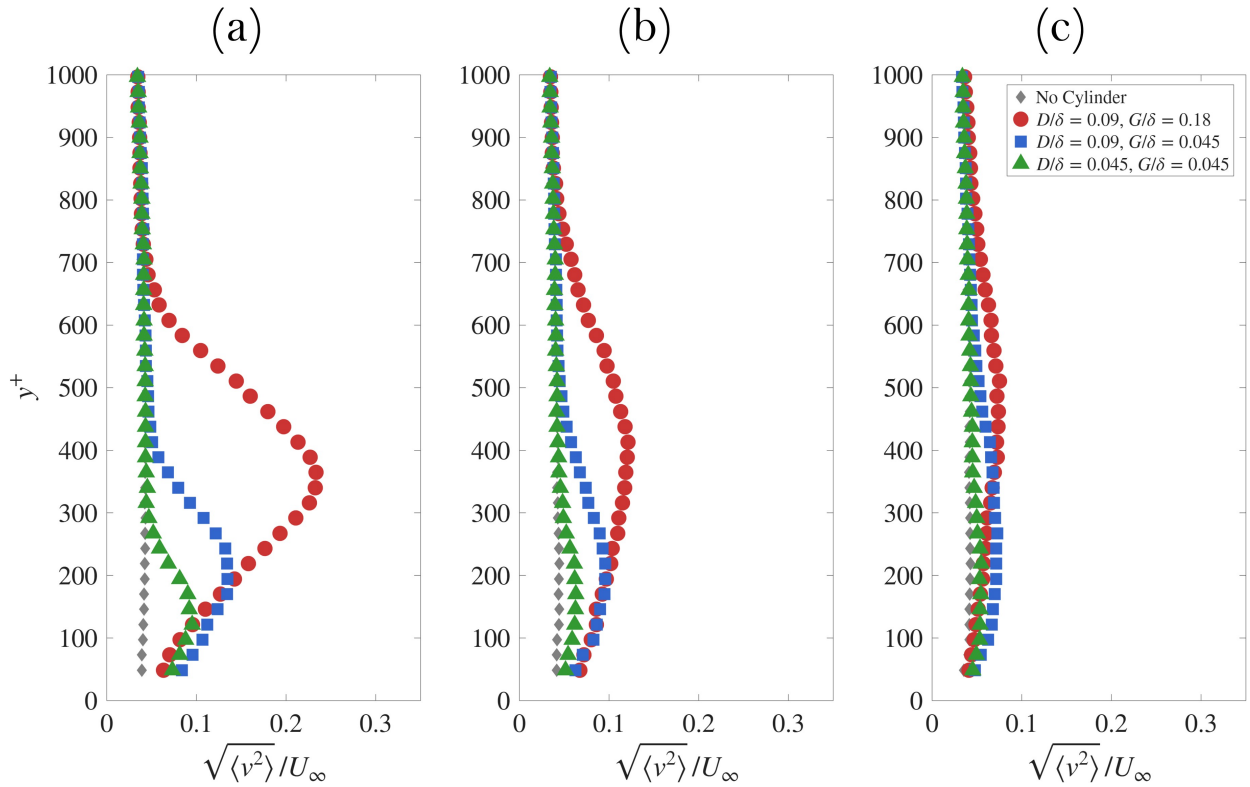


Figure 6. Wall-normal profiles of wall-normal turbulent intensity $\sqrt{\langle v^2 \rangle} / U_\infty^2$ at (a) $x/\delta = 0.5$, (b) $x/\delta = 1.2$, and (c) $x/\delta = 2.2$ for unperturbed, $D/\delta = 0.09$; $G/\delta = 0.18$ (red), $D/\delta = 0.09$; $G/\delta = 0.045$ (blue), and $D/\delta = 0.045$; $G/\delta = 0.045$ (green).

hanced wall-normal momentum transport. This case exhibits the highest magnitude of turbulence intensity among all configurations, with the elevated region persisting far downstream.

When the gap is reduced ($G/\delta = 0.045$, Figure 5(c)), the increase in v_{rms} is weaker in magnitude compared to the high-gap case and remains confined below $y^+ = 400$. Another feature of the low-gap configuration is that the high-turbulence region in the wake initially extends to and remains connected to the wall. The elevated v_{rms} levels span the entire gap region, suggesting an interaction between the cylinder wake and the near-wall turbulent structures.

When the cylinder diameter is reduced but the gap is held constant ($D/\delta = 0.045$, $G/\delta = 0.045$, Figure 5(d)), the wake weakens further and the turbulence intensity levels decrease. As in the $D/\delta = 0.09$ case, the elevated v_{rms} values bridge the gap region and extend to the wall, although the streamwise extent is reduced.

The streamwise evolution of the wall-normal turbulence intensity is examined further in Figure 6, which presents wall-normal profiles of v_{rms}/U_∞ at three streamwise locations: $x/\delta = 0.5$, 1.2, and 2.2. For the large cylinder, large gap ($D/\delta = 0.09$, $G/\delta = 0.18$, red circles), the peak v_{rms} value at $x/\delta = 0.5$ is the largest among all cases, reaching approximately 0.25 at $y^+ = 360$, slightly

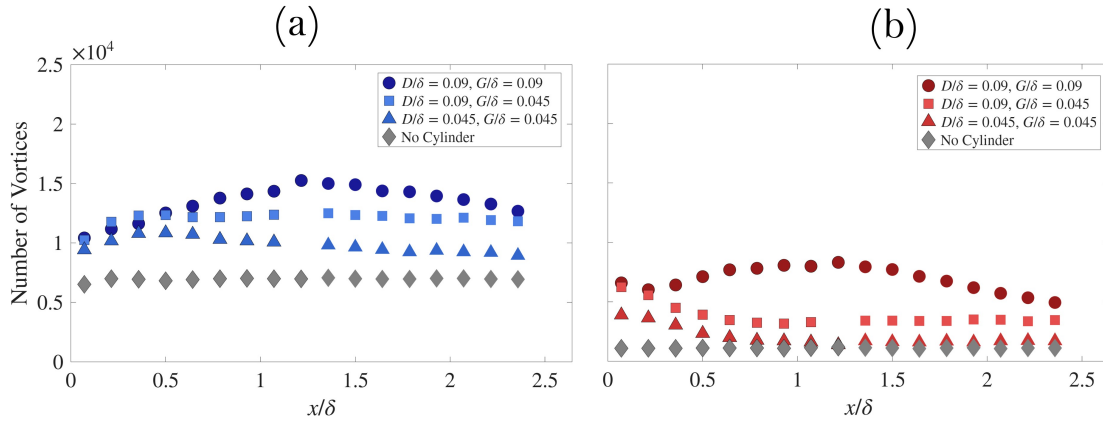


Figure 7. Streamwise evolution of total vortex count integrated over y/δ for (a) negative (clockwise) vortices and (b) positive (counterclockwise) vortices. Results are shown for all cylinder configurations. The unperturbed level is indicated by the gray diamond.

above the cylinder center height ($y^+ = 338$). Downstream at $x/\delta = 1.2$ and 2.2 , the peak gradually decreases in magnitude while the profile broadens significantly in the wall-normal direction, indicating wall-normal spreading of the turbulent disturbance away from the wake core. It is also noted that the profile peak moves away from the wall with increasing downstream distance.

For the large cylinder with smaller gap ($D/\delta = 0.09$, $G/\delta = 0.045$, blue squares), the peak v_{rms} at $x/\delta = 0.5$ is weaker than in the high-gap case, reaching approximately 0.13, and is initially located at $y^+ \approx 200$, which is significantly above the cylinder center height of $y^+ = 135$. Another feature of this configuration is that the turbulence intensity closer to the wall ($y^+ = 50$ to $y^+ = 150$) is larger than in the large gap case, suggesting an interaction between the cylinder wake and the near-wall region that produces the increased fluctuations. Further downstream, the profiles exhibit a progressive broadening away from the wall and decay of the peak.

For the small cylinder with small gap ($D/\delta = 0.09$, $G/\delta = 0.045$, green triangles), the peak v_{rms} at $x/\delta = 0.5$ is the smallest among the three cylinder cases and occurs closer to the wall than in the large cylinder case. The overall shape of this profile qualitatively resembles that of the larger low-gap cylinder, but with reduced magnitude and a more rapid decay towards the unperturbed levels.

3.3. Streamwise Distribution of Vortices

We first examine how the total number of identified vortices and the circulation contained within them evolve along the streamwise direction. Figure 7 presents the total number of (a) negative (clockwise) and (b) positive (counterclockwise) vortices, integrated over the wall-normal direction, as a function of x/δ for all cases tested. The unperturbed case is shown in gray diamonds for reference.

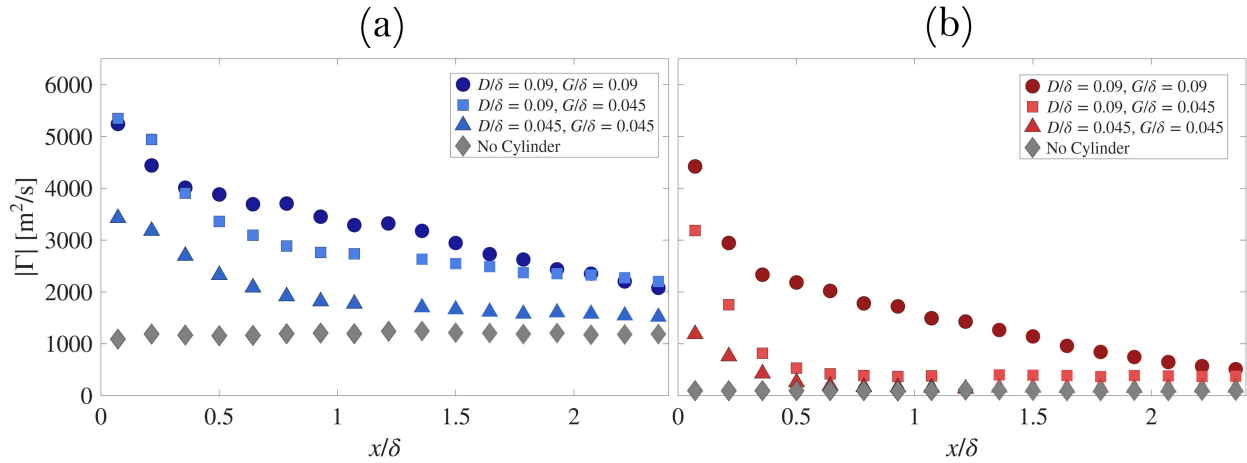


Figure 8. Streamwise evolution of total circulation (sum of $|\Gamma|$) for (a) negative and (b) positive vortices.

In all perturbed cases, the total vortex count exceeds unperturbed levels throughout the measurement domain. This observation is consistent with the turbulent intensity results, confirming that the cylinder's influence on the coherent structures is persistent. In all cases, negative vortices consistently outnumber positive vortices, reflecting the mean clockwise shear imposed by the wall.

All three cylinder cases yield similar initial increases in the number of negative vortices. For the large cylinder with a large gap ($D/\delta = 0.09$, $G/\delta = 0.18$), the number of negative vortices then increases at an almost constant rate up to a value near 15000 at $x/\delta = 1.2$, after which it slowly decreases. For reference, the peak value is more than twice the value of 7000 in the unperturbed case. For the large cylinder with smaller gap ($D/\delta = 0.09$, $G/\delta = 0.045$), the negative vortex count rises to a lower peak value compared to the high-gap case, reaching approximately 12000 at $x/\delta = 0.35$, and then stabilizing near that value through $x/\delta = 2.5$. For the small cylinder with low gap ($D/\delta = 0.045$, $G/\delta = 0.045$), the peak also occurs at $x/\delta = 0.35$, reaching a value lower than both large-cylinder cases, after which it decreases slowly to approximately 9000 at $x/\delta = 2.5$.

Considering positive vortices, the large cylinder with large gap ($D/\delta = 0.09$, $G/\delta = 0.18$), yields a number that decreases over the first two data points and then increases to a peak of approximately 8000 at $x/\delta = 1.2$, after which it decreases to approximately 5000 at $x/\delta = 2.5$. For reference, the unperturbed level is 1100. By contrast, the large cylinder with low gap ($D/\delta = 0.09$, $G/\delta = 0.045$), yields a count that decreases from the first data position and reaches a stable value around 3400 at $x/\delta = 0.8$. For the small cylinder with low gap ($D/\delta = 0.045$, $G/\delta = 0.045$), the initial number is smaller, but the pattern resembles that of the larger low-gap cylinder albeit with fewer vortices. It reaches a stable value near 1600 also at $x/\delta = 0.8$.

The circulation associated with these vortices tells a different story. Figure 8 presents the total circulation (sum of absolute circulation) within (a) negative and (b) positive vortices as a function of x/δ , with units of m^2/s . Unlike vortex count, which rises and/or plateaus in some cases, to-

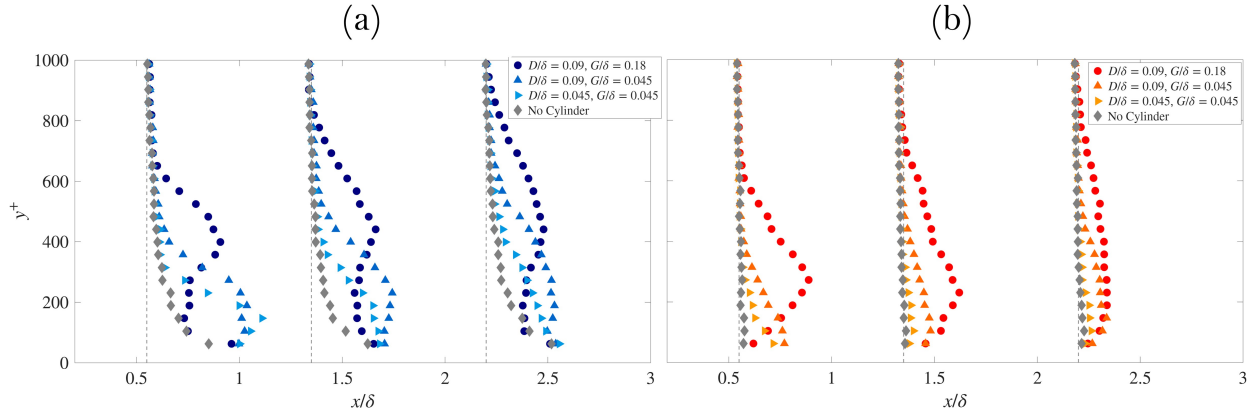


Figure 9. Wall-normal profiles of vortex count at $x/\delta = 0.55, 1.35$, and 2.2 for large cylinder ($D/\delta = 0.09$) at high gap ($G/\delta = 0.18$), large cylinder at low gap ($G/\delta = 0.045$), and small cylinder ($D/\delta = 0.045$) at low gap. (a) Negative (clockwise) vortices. (b) Positive (counterclockwise) vortices. Unperturbed profiles are shown in gray for reference.

tal circulation decreases monotonically with downstream distance for all cases. This decoupling between count and circulation indicates that vortices weaken (lose circulation) on average before they become undetectable, either through viscous dissipation or reorientation out of the measurement plane.

For the large cylinder at both high and low gaps, the curves for total negative circulation largely overlap and decrease at similar rates with downstream distance. In contrast, the small cylinder case has a lower initial circulation and decays to a value of approximately $1500 \text{ m}^2/\text{s}$ by $x/\delta = 2.5$, approaching but remaining above the unperturbed level of $1200 \text{ m}^2/\text{s}$.

For the large cylinder with large gap, positive circulation is initially higher and decreases more slowly compared to the low-gap case. The positive circulation for the large cylinder with small gap is initially much higher than the unperturbed value, but then, it decays very rapidly by $x/\delta = 0.8$ to $380 \text{ m}^2/\text{s}$ and stabilizes slightly above the unperturbed level of $100 \text{ m}^2/\text{s}$. The small cylinder, small gap case has a lower initial value, but then stabilizes at the same $x/\delta = 0.8$ location to a value of approximately $150 \text{ m}^2/\text{s}$, only slightly above the unperturbed level.

3.4. Wall-Normal Distribution of Vortices

To examine spatial organization, we turn to wall-normal profiles at three streamwise locations: $x/\delta = 0.55, 1.35$, and 2.2 (Figure 9). The positive vortex counts in Figure 9(b) are scaled by a factor of two relative to negative counts for better visualization.

The wall-normal distributions of vortices in the unperturbed case (gray diamonds) are consistent with the canonical trends reported by Wu & Christensen (2006) (see their Figure 4). Prograde (negative) vortices are more numerous and peak within the log layer ($y/\delta \approx 0.1 - 0.2$), while

retrograde (positive) vortices are fewer in number and more uniformly distributed across the wall-normal domain.

Figure 9(a) presents the distributions of negative vortices. For the large cylinder with a high gap ($D/\delta = 0.09$, $G/\delta = 0.18$), the negative vortex count at $x/\delta = 0.55$ is elevated above unperturbed levels between $y^+ \approx 100$ and 700, peaking at $y^+ \approx 400$, near the top of the cylinder (which spans $y^+ = 270$ to 405). Below $y^+ \approx 100$ and above $y^+ \approx 700$, counts remain near unperturbed levels. The elevated region expands to a range from $y^+ \approx 60$ to 800 by $x/\delta = 1.35$ and up to $y^+ \approx 900$ by $x/\delta = 2.2$, with the peak shifting upward to $y^+ \approx 450$.

When the gap is decreased ($D/\delta = 0.09$, $G/\delta = 0.045$), the peak value is larger, even though the total number of vortices at this streamwise location is similar (see Figure 7). The same spreading effect is observed on the upper side of each profile, but unlike the high-gap case, the peak y -location does not shift outward with downstream distance, remaining at $y^+ \approx 190$, which is close to, though slightly lower than, the top of the cylinder (spanning from $y^+ = 67$ to 202). For the smaller cylinder with a low gap ($D/\delta = 0.045$, $G/\delta = 0.045$), the profile exhibits the highest peak among all cases, despite having fewer total vortices than the larger cylinder. This likely occurs because, at this peak location, there are more unperturbed vortices present, in addition to any vortices associated with the cylinder wake.

Figure 9(b) presents the distribution of positive vortices. For the large cylinder with large gap, the number of positive vortices first exhibits a clear peak at $y^+ \approx 270$. The peak then decreases in magnitude and the profile spreads upward with increasing downstream distance. The region where positive vortex counts exceed unperturbed levels expands from a maximum $y^+ \approx 650$ at $x/\delta = 0.55$ to $y^+ \approx 850$ at $x/\delta = 2.2$.

For the large cylinder with small gap, the total number of positive vortices is smaller and approximately constant across all three profile locations (see Figure 7). The profiles show that the distribution of positive vortices shifts upward across the field of view, and the upper limit of the perturbation also shifts upward eventually to a location near $y^+ = 600$. For the case with the smaller cylinder, the positive vortex counts are small, but initially largest near the wall.

3.5. Comparison Between v_{rms} and Vortex Number Profiles

The wall-normal turbulent intensity v_{rms} can be interpreted as a signature of vortex-induced motions. Figure 10 directly compares the v_{rms} profiles and the total (negative + positive) vortex number profiles at three streamwise locations ($x/\delta = 0.55$, 1.35, and 2.2) for all three cylinder configurations. For visual comparison, both quantities are normalized by their respective peak values within each case: v_{rms} profiles are normalized by the maximum v_{rms} value across the three streamwise locations, and vortex count profiles are normalized by the maximum vortex count across the same three locations. In each subfigure, filled markers represent normalized v_{rms} , while hollow

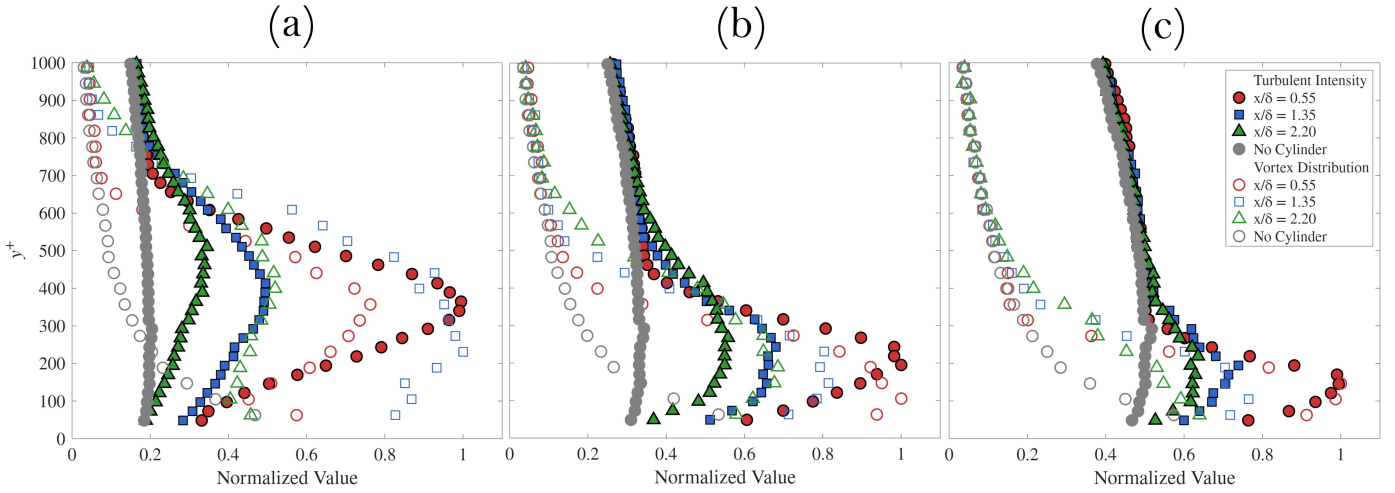


Figure 10. Comparison between wall-normal turbulent intensity v_{rms}/U_∞ and total vortex number profiles across three streamwise locations: (a) $D/\delta = 0.09$; $G/\delta = 0.18$, (b) $D/\delta = 0.09$; $G/\delta = 0.045$, and (c) $D/\delta = 0.045$; $G/\delta = 0.045$. Profiles are normalized by the peak values for each case.

markers represent normalized vortex count. Gray markers indicate the baseline no-cylinder case (averaged across all positions).

For $D/\delta = 0.09$, $G/\delta = 0.18$, the peak in vortex count and the peak in v_{rms} coincide at $y^+ \approx 360$ at $x/\delta = 0.55$, and the outer parts of the profiles are similar. The profile shapes differ closer to the wall however. At $x/\delta = 1.35$ and 2.2 , the peak in vortex count lies at $y^+ = 360$, then 400 . By contrast, the v_{rms} peak migrates upward to $y^+ \approx 415$ and 460 at $x/\delta = 1.35$ and 2.2 respectively. The outer limit of the perturbation compared with the ‘no cylinder’ case, which increases with downstream distance, is fairly consistent for both quantities. Between the profile peak locations and the wall, however, the vortex count profiles remain elevated compared with the v_{rms} profiles as might be expected given the differing unperturbed profile shapes in that range.

For $D/\delta = 0.09$, $G/\delta = 0.045$ at $x/\delta = 0.55$, the peak locations of v_{rms} and vortex count do not overlap at $x/\delta = 0.55$: the vortex count peak is near $y^+ = 100$, well below the center of the cylinder, while the v_{rms} peak is near $y^+ = 200$. This result suggests that, although many vortices are identified close to the wall, they are not contributing strongly to wall-normal motions. Further downstream, at $x/\delta = 1.35$ and 2.2 , the peaks of the two quantities are both closer to $y^+ = 200$, and the profiles for both quantities broaden in a similar fashion.

For the smaller cylinder ($D/\delta = 0.045$, $G/\delta = 0.045$), a good correlation between v_{rms} and vortex count is observed at $x/\delta = 0.55$ and 1.35 . However, by $x/\delta = 2.2$, the vortex count profile no longer exhibits a distinct peak and instead is maximized at the point closest to the wall, similar to the trend for the unperturbed case (open gray symbols). This return toward the baseline distribution is consistent with the earlier observation that the small cylinder’s influence on the flow decays more rapidly than that of the large cylinder, as shown in Figures 7 and 8.

The close agreement between the two different measurements, one based on wall-normal motions and the other on direct vortex identification, supports the interpretation that the elevated v_{rms} values downstream of the cylinders likely correspond with vortex-induced motions in the perturbed flow.

4. Conclusions

The downstream evolution of vortices generated by small cylinders ($D/\delta = 0.045$ and 0.09) embedded in the logarithmic region of a turbulent boundary layer were investigated for gap heights of $G/\delta = 0.045$ and 0.18 . Two-component velocity fields were acquired using planar PIV from which mean the mean and fluctuating fields were calculated. Coherent vortex circulation and spatial distribution was quantified using a Q -criterion vortex identification. Several trends were observed to depend on the presence of the cylinder, its size, and its distance from the wall.

The number of identified negative and positive vortices increases strongly downstream of the cylinder and remains above unperturbed levels through the measurement domain for all cases tested. Larger cylinders create a larger deficit in the mean wake and higher magnitude turbulence intensity relative to the unperturbed profiles. For all cases examined, the mean wake deficit and elevated v_{rms} levels remain observable until $x/\delta = 2.5$.

Negative (clockwise) vortices consistently outnumber positive (counterclockwise) vortices, reflecting the mean clockwise shear imposed by the wall. Vortex count and total circulation evolve differently: while vortex count continues to increase or remains elevated with downstream distance for most cases, total circulation decays monotonically downstream of the cylinder for all cases. This suggests that individual vortices weaken, reorient, or split into multiple vortices before falling below the Q -criterion threshold.

Negative shear near the wall appears to suppress positive vortices shed from the cylinder more strongly than negative vortices. For a larger gap ($G/\delta = 0.09$), the number of positive vortices increases just downstream of the cylinder before starting to decrease around $x = 1.25\delta$. For both cylinders at the smaller gap ($G/\delta = 0.045$), positive vortices decrease in number from the first data point.

Reducing the cylinder diameter from $D/\delta = 0.09$ to 0.045 (while holding $G/\delta = 0.045$) produces weaker and shorter-lived disturbances. The smaller cylinder's mean velocity profile nearly returns to the unperturbed state by $x = 2.4\delta$, and its positive vortex distribution relaxes to unperturbed levels at the same downstream location. However, negative vortices remain elevated even for the smaller cylinder, suggesting that clockwise-signed disturbances induced by even small obstacles can persist over long distances when the obstacle is positioned close to the wall.

Comparison between v_{rms} and vortex count profiles shows good general correspondence, support-

ing the interpretation that increases in wall-normal motions likely result primarily from vortex-induced motions.

In future work, we plan to extend the measurement domain farther downstream to better understand the dependence of recovery on D/δ and G/δ . Also, time-resolved PIV would improve our understanding of how individual vortices form, weaken, or split.

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