

Effects of freestream turbulence on the wakes of circular and square cylinders

Leon Li  and R. Jason Hearst ^{*}

Department of Energy & Processing Engineering, Norwegian University of Science & Technology, Kolbjørn Hejes Vei 2, 7034 Trondheim, Norway



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Two cylinder geometries, circular and square, were subjected to four distinct inflows to investigate the effects of freestream turbulence (FST) on their wake development. The wake flow fields were measured using planar particle image velocimetry with a large field of view, covering a contiguous area up to 20 cylinder diameters (D) downstream of the wake-generating body. The experiments were conducted at a Reynolds number of $Re_D = 33\,000$. The turbulent inflows were generated using an active grid, which produced freestream turbulence intensities ranging from 1.1% to 13.8%. The integral scales of the turbulence varied between $4.32D$ and $7.86D$. The findings demonstrate that FST facilitates the recovery of the wake velocity deficit and promotes an earlier trend towards self-similarity in the velocity profile. Moreover, a reduction in the coherence of the shed vortices is observed in the wake as FST increases, resulting in a lower average number of coherent shed vortices and a transfer of energy from the proper orthogonal decomposition modes associated with vortex shedding to modes associated with the background turbulence. These observations explicitly demonstrate that the enhanced mixing due to elevated freestream turbulence facilitates faster wake recovery, loss of coherence of the shed vortices, approach to self-similarity of velocity statistics, and significant alterations in the instantaneous wake flow field.

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I. INTRODUCTION

The interaction of freestream turbulence with a cylinder is a ubiquitous combination that can be found throughout the natural and built environment. The influence of freestream turbulence on flow past a cylinder starts with the boundary layer on the cylinder itself, which in turn changes the aerodynamic forces acting on the cylinder and the flow in the immediate wake. The cylinder geometry also plays an important role in how these phenomena behave. Furthermore, the turbulence continues to interact with the cylinder wake in the intermediate and far field, thereby changing the wake characteristics and behavior. For nearly a century, there has been detailed experimental and numerical investigations to understand the physics of this problem.

In the early work by Fage and Warsap [1], the effects of freestream turbulence (FST) on the drag of a circular cylinder were examined. FST was generated using a rope netting, and the cylinder was positioned at streamwise locations of $x_1/M = 24, 32$, and 49 , where x_1 denotes position along the mean flow direction, and M denotes the mesh length of the netting, i.e., the center-to-center spacing between adjacent grid (or net) bars. The Reynolds numbers, based on the cylinder diameter D , ranged from $Re_D = 40\,000$ to $230\,000$. The findings indicated that freestream turbulence promotes

^{*}Contact author: jason.hearst@ntnu.no

early onset of the drag crisis, characterized by a sudden and significant drop in the drag coefficient. For a smooth circular cylinder with minimal FST, this drag crisis typically occurs between $10^5 \leq \text{Re}_D \leq 10^6$ (e.g., Refs. [2–4]), where the drag coefficient decreases from around 1.2 to around 0.3. For the most turbulent case in Fage and Warsap [1], the onset of the drag crisis is decreased to $\text{Re}_D \approx 4.7 \times 10^4$. This early evidence suggested that FST has a measurable impact on the flow field around a cylinder by inducing artificial transition of the boundary layer on the cylinder from laminar to turbulent, similarly to the effect of surface roughness on a cylinder (e.g., Refs. [5,6]). Here we use the terms “subcritical” and “supercritical” to denote the flow regimes before and after the drag crisis, with the transitional stage in between being referred to as the “critical” regime. The present study investigates wake flow in the subcritical regimes, as will be shown in later sections. Bishop and Hassan [7] investigated the lift coefficient in addition to the drag coefficient. Within the tested Reynolds number range ($3600 \leq \text{Re}_D \leq 11\,000$), they found that the time-averaged lift coefficient exhibited weak dependence on the Reynolds number, while the drag coefficient remained nearly constant. The maximum Reynolds number examined by Bishop and Hassan [7] did not reach the critical regime, explaining the weak dependence of the aerodynamic properties on the Reynolds number in that range. Subsequent studies by Cheung and Melbourne [8], Surry [9], and Kiya *et al.* [10] showed that increasing the freestream turbulence intensity has the overall effect of artificially increasing the effective Re_D across all three regimes, or in other words, it promotes the transition from subcritical to supercritical. For instance, Kiya *et al.* [10] observed that the onset of the drag crisis for their four turbulent inflow cases are all between $2 \times 10^4 \leq \text{Re}_D \leq 5 \times 10^4$. The maximum turbulence intensity reached in the three aforementioned studies ranges from 10% to 18.5%, and it is achieved through passive turbulence grids. However, even when the inflow turbulence intensity is low ($\sim 1\%$), transition in the boundary layer on the cylinder is promoted, leading to significant changes in the surface pressure distribution and the Strouhal number bandwidth [11–13].

Changes in the surface pressure distribution and the Strouhal number characteristics indicate changes in the aerodynamic forces acting on the cylinder. Vickery [14], using a passive turbulence grid, saw that elevated FST reduced the root-mean-square (RMS) of the lift fluctuations by about 50% for a square cylinder. The inflow had 10% turbulence intensity and a normalized integral length scale of $L_{11}/D \approx 1.33$ at the cylinder mounting location. Here L_{11} denotes the integral length scale of u_1 in x_1 and D denotes the square side length of the cylinder. More recently, Blackburn and Melbourne [15] saw that elevated FST can cause the lift coefficient energy spectrum to transfer energy from a Strouhal number of around 0.2, associated with the vortex shedding, to lower frequencies. Khabbouchi *et al.* [16] took hot-wire measurements in the separated shear layer behind a circular cylinder for different FST conditions and Reynolds numbers and found that increasing the FST has the effect of accelerating the breakdown of the shear layer vortices. Kankanwadi and Buxton [17,18] investigated a scalar interface demarcating fluid tagged with a high Schmidt number scalar in the immediate wake from the freestream turbulence, with a focus on the entrainment mass flux across the identified interface. A fractal grid was used to produce the FST. The introduction of FST greatly affected the development of the interface and the entrainment process, in one case even reversing the flux direction. However, in their studies, the Re_D was only $O(10^3)$ and the cylinder itself was placed near the grid where the Appendices show mean flow inhomogeneity at the cylinder location.

Cylinder cross-sectional geometry also plays an important role. Tamura and Miyagi [19] examined square cylinders with various corner shapes exposed to different inflow conditions. They found that rounded or chamfered corners decrease the overall drag for the same flow conditions, due to the reduced wake width, and that freestream turbulence can cause the separated shear layer to reattach on the cylinder. In a study by Li *et al.* [20] on the effect of turbulence on the unsteady gust loading of a 5:1 rectangular cylinder, it was observed that elevated freestream turbulence reduces the separation bubble size on the cylinder side face and results in a stronger spanwise correlation of the pressure fluctuations. These effects by the freestream turbulence are not limited to a planar wake, as Hearst *et al.* [21] showed that increasing freestream turbulence intensity can also promote reattachment of the top of a wall-mounted cube. Additionally, Li *et al.* [22] found that freestream

turbulence increases the vortex formation length in the near wake of a square cylinder and weakens the vortex shedding process. However, their measurements were limited to $x_1/D \leq 4$, and they did not investigate the spatial development of the wake farther downstream.

Looking past the near wake, Eames *et al.* [23] found that for $Re_D \sim O(10^3)$, if $L_{11}/D \gg 1$, then the centerline velocity deficit, U_s , and the wake half-width, ℓ , actually vary as x_1^{-1} and x_1^1 , as opposed to the canonical behavior of varying as $x_1^{-1/2}$ and $x_1^{1/2}$, respectively (e.g., p. 148 in Ref. [24]). In their study, the freestream turbulence intensity was 18% with $L_{11}/D \approx 6.8$. We seek to also investigate this behavior through the present study but with Re_D an order of magnitude higher and with an inflow with less inhomogeneity to see if this behavior is influenced by the Reynolds number and/or the flow homogeneity. Enhanced wake expansion due to increased turbulent entrainment has also been reported by Kankanwadi and Buxton [25]. Similar increases in the velocity recovery has been reported for axisymmetric wakes such as that of a sphere [26] and a wind turbine [27–29], all of which reported a decay rate of x_1^{-2} when exposed to large-scale turbulence. Faster velocity recovery has also been reported for porous disks under the influence of elevated FST [30]. Turbulence can also cause a breakdown of the periodicity of the vortices in a cylinder wake, as shown by De Jesús *et al.* [31], who immersed a cylinder inside a turbulent boundary layer.

Table I summarizes a spectrum of experimental studies from the literature, including the aforementioned studies on the effect of freestream turbulence on the flow around cylinders. In these studies, passive grids were used extensively as the means to generate the different flow conditions. While they can generate relatively homogeneous and isotropic turbulence (HIT) in transverse planes, passive grids are limited by the maximum turbulence intensity they can generate while approximating HIT. Kiya *et al.* [10] reached 18.5%, but this was done at the cost of having the cylinder only $6.7M$ downstream of the grid, where grid turbulence typically exhibits non-negligible inhomogeneity (e.g., Refs. [32–34]). The studies by Kankanwadi and Buxton [17,18] were similarly performed with the cylinder in a region of the flow where there were mean flow inhomogeneities (although their entrainment measurements are performed in a more homogeneous region) and in a flow where the dissipation is known to follow a nonequilibrium scaling as opposed to the classical dissipation scaling [33,35]. Thus, while insightful on the intricacies of transport across the scalar interface, the dynamics of the turbulent flow may differ from those in “canonical” HIT. With the advent of active grids, beginning with Makita [36], a new tool emerged that could generate significantly larger-scale freestream turbulence while maintaining flow homogeneity and isotropy comparable to those of passive grids. Several studies have already used active grids to investigate the effect of high levels of freestream turbulence on objects and flow phenomena of different complexity (e.g., Refs. [37–39]). As such, an active grid will be used in the present study to generate large-scale FST while keeping it relatively homogeneous and isotropic.

The extensive review studies into the behavior of flow around cylinders (e.g., Refs. [47–51]) demonstrate that there are a plethora of studies on cylinder wakes of various cross-sectional geometries and that the topic has come a long way over the past few decades. Both experimental and numerical investigations have revealed increasingly complex insights into the physics of flows behind a cylinder. Wake flow in the subcritical to critical regimes are interesting due to the development of shear layer instability in the near wake and the onset of three-dimensional (3D) coherent structures [49,50]. With the advent of modern high-powered lasers and high-resolution cameras, it is now possible to image relatively large fields of view in the wake of a cylinder in these flow regimes, with moderately high Reynolds numbers of $O(10^4)$ or higher. To date, there has been a lack of systematic investigations into the general wake characteristics of different cylinder geometries under the influence of different turbulent inflow conditions [51]. Most studies found in the literature focus on the pressure and aerodynamic force fluctuations around the cylinder, the Strouhal number of the vortex shedding process, or the development of the turbulence in the wake without the addition of freestream turbulence, as can be seen in Table I. There is thus a gap in our understanding of how the wake behaves under the influence of FST. For example, it has been shown that FST causes faster wake recovery (e.g., Refs. [23,26,28,30]) and an earlier breakdown of the von Kármán vortex street [31]. However, there is a need to extend these results to higher

TABLE I. Summary of representative literature; this list may not be exhaustive. For cylinder geometry, CIR denotes circular, SQR denotes square, and REC(A) denotes an extruded rectangle with aspect ratio A . If a turbulence grid was used, then the closest position of the cylinder relative to the grid is provided in the x_1/M column. For measurement types, P denotes surface pressure measurements; C_L , C_D , and C_f denote lift, drag, and surface friction measurements, respectively; HW denotes hot-wire; LDV denotes laser Doppler velocimetry; ADV denotes acoustic Doppler velocimetry; PIV denotes particle image velocimetry; and PLIF denotes planar laser-induced fluorescence. Information that could not be sourced in the original material is marked with “–”; this is differentiated from “N/A” which marks a field that is not applicable to a specific study.

Study	Cylinder geometry	Re_D [$\times 10^3$]	u'_1/U_∞ [%]	x_1/M	Measur. types	x_1/D range
Fage and Warsap [1]	CIR	40–230	–	–	P , C_D	N/A
Bishop and Hassan [7]	CIR	3.6–11	~ 0	N/A	C_L , C_D	N/A
Bloor [40]	CIR	0.2–50	~ 0	N/A	HW	[0 57]
Vickery [14]	SQR	40–160	10	–	C_L , C_D	N/A
Surry [9]	CIR	33.8	2–15	–	P , C_L , C_D	N/A
Kiya <i>et al.</i> [10]	CIR	26.5–39.8	1.4–18.5	6.7	P , C_D	N/A
Cheung and Melbourne [8]	CIR	100–1000	0.4–9.1	–	P , C_L , C_D	N/A
Kwok [11]	CIR	83–550	0.1–9	N/A	P , C_D	N/A
Norberg and Sundén [12], Norberg [13]	CIR	20–300	0.1–1.4	106	P , C_D , C_f , HW	[0 3]
Matsumura and Antonia [41]	CIR	5.8	~ 0	N/A	HW	[10, 20, 40]
Lyn <i>et al.</i> [42]	SQR	21.4	2	N/A	LDV	[–0.5 8]
Blackburn and Melbourne [15]	CIR	100–500	0.6–18	3	C_L	N/A
Tamura and Miyagi [19]	SQR	30	6.5–14	5	C_L , C_D	N/A
Saha <i>et al.</i> [43]	SQR	8.7–17.6	~ 0	N/A	HW	[1 6]
Yiu <i>et al.</i> [44]	CIR	2.5–10	~ 0	N/A	HW	[10, 20, 40]
Eames <i>et al.</i> [23]	CIR	1.3–2.1	18	N/A	ADV	[2 10]
Khabbouchi <i>et al.</i> [16]	CIR	4.5–47	0.25–6.2	–	HW	[0.2 1.6]
Kankanwadi and Buxton [17, 18]	CIR	4	2–14	2	PIV, PLIF	[37 41]
Kankanwadi and Buxton [25]	CIR	12	2–14	3	PIV, PLIF	[–4 5]
Chen and Buxton [45]	CIR	3.8	2–14	2	PIV, PLIF	[5 40]
Chen and Buxton [46]	CIR	3.8	2–14	2	PIV, PLIF	[6.5, 10, 20, 30, 40]
Li <i>et al.</i> [20]	REC(5)	33	3–10	12.7	P	N/A
Li <i>et al.</i> [22]	SQR	21	6–20	11.8	P , PIV	[1 4]
De Jesús <i>et al.</i> [31]	CIR	1.1	–	N/A	PIV	[0 74]
Present work	CIR, SQR	33	1.1–13.8	64	PIV	[0.7 20]

Re_D as low-Reynolds-number flows are known to be more sensitive to finite-Reynolds-number effects [52], and thus it is unclear if previous results are relevant at Reynolds numbers that are applicable in engineering and environmental flows. Moreover, the proximity of the cylinder to the turbulence generator in previous studies (see Table I) produces further ambiguity with respect to whether some of these findings are idiosyncratic or general. It is the aim of the present study to address this research gap by providing a systematic investigation into the influence of different incoming, approximately homogeneous and isotropic, turbulent flows on the wake of cylinders with different cross-sectional geometries, at moderate Reynolds numbers, capturing the entire flow field instantaneously up to $x_1/D = 20$ to comment on the existence of coherent vortices, dominant spatial modes, and the approach to self-similarity.

II. EXPERIMENTAL SETUP

A. Facility and apparatus

The experiments were conducted in the large low-speed wind tunnel at the Norwegian University of Science and Technology. The wind tunnel features a closed-loop design, with a centrifugal

fan located downstream of the test section and diffuser. The test section itself has dimensions of $2.71 \text{ m} \times 1.80 \text{ m}$ in cross-sectional area and is 11.15 m in length. To ensure a steady bulk flow and compensate for boundary layer growth inside the test section, the ceiling of the tunnel is adjustable such that a near-zero-pressure gradient can be achieved. The floor, ceiling, and one side of the test section are made of float glass and clear acrylic panels, providing optical access to three sides of the test section. The maximum flow velocity attainable in the wind tunnel is approximately 22 ms^{-1} . For the present study, the freestream velocity was maintained at $U_\infty \approx 11 \text{ ms}^{-1}$.

The flow conditioning at the time of this measurement campaign consisted of a honeycomb and a set of meshes located upstream of the contraction. These components ensure a freestream turbulence intensity in the empty tunnel of approximately $u'_1/U_\infty \approx 1\%$ at the test velocity; note that more recent modifications to the flow conditioning have dropped the background turbulence intensity to $\sim 0.25\%$. Here Reynolds decomposition is employed to separate the velocity (u_i) into its mean (U_i) and fluctuating components (u'_i), viz. $u_i = U_i + u'_i$.

The active grid employed in the experiment has dimensions of $2.71 \text{ m} \times 1.80 \text{ m}$, covering the entire cross-sectional area of the test section. It consists of 90 vertical and horizontal bars, each equipped with an independently actuated stepper motor. The bars hold square-shaped aluminium wings arranged in a space-filling pattern, and the mesh length, defined as the separation between the centerlines of the bars, is $M = 0.1 \text{ m}$. This is the same grid used by Kildal *et al.* [53]. The grid was operated at a Reynolds number of approximately $\text{Re}_M = U_\infty M/\nu \approx 6.6 \times 10^4$ for this measurement campaign. Control of the stepper motors is achieved using serial commands issued via MATLAB. Hearst and Lavoie [54] determined that the freestream velocity U_∞ and the wing rotation rate Ω have the most significant influence on the generated freestream turbulence properties for a given active grid configuration. As the present study maintains a near-constant value for U_∞ , we varied Ω to produce three different inflow conditions. Three sets of stepper motor rotation rates were randomly generated from top-hat distributions centered at $\Omega = 1, 2$, and 5 Hz . The bandwidth of the top-hat distributions was set to $\omega = \pm 0.5\Omega$. Additionally, for the $\Omega = 5 \text{ Hz}$ case, only the vertical bars were rotated while keeping the horizontal bars stationary and their wings feathered to align with the mean flow. This configuration was employed to reduce the freestream turbulence intensity by decreasing the time-averaged blockage ratio of the grid. Together with a reference case, REF, where the active grid is removed, we have a total of four inflow conditions.

To gather statistics of the inflow conditions, constant temperature anemometry was performed using a Dantec 55P11 hot-wire probe with a Dantec Streamline Pro anemometer. The probe was positioned at the center of the empty test section in x_3 , at the leading edge position of the cylinders ($x_1/M \approx 63.8$). The probe has a sensing length of 1.25 mm , and the wire diameter is $5 \mu\text{m}$. The sampling frequency was set to 75 kHz , and the anemometer's internal low-pass filter was set to 30 kHz . This is more than sufficient to resolve the full spectra of the turbulent velocity fluctuations for all the test cases, which have Kolmogorov frequencies of approximately 10 kHz .

Two different cylinder geometries were tested: a circular cylinder with a diameter $D = 0.05 \text{ m}$ and a square cylinder with a side length of the same size. For simplicity, both the circular cylinder diameter and the square cylinder side length will be referred to as D subsequently. The cylinders are positioned transversely in the test section, spanning its entire width, thus eliminating the need for endplates. They are supported by four vertical struts located at the 4%-, 25%-, 75%-, and 96%-span positions, leaving the central 50% of the cylinder span ($1.35 \text{ m} = 27D$) unobstructed to the freestream flow. The centers of the cylinder cross sections are located $0.75 \text{ m} = 15D$ above the floor of the test section and $64M$ downstream from the active grid. To provide stiffness and limit vibrations, steel guy-wires are attached to the two inner support struts. The cylinders are constructed from aluminium and have been sanded to at least 400-grit to ensure aerodynamic smoothness. Black paint is applied to the central span of the cylinders to reduce laser reflections and to further enhance surface smoothness. The overall blockage ratio of the setup is approximately 5.4% , which is below the 6% threshold suggested by West and Apelt [55] for the application of wind tunnel blockage correction. The Reynolds number based on the cylinder diameter is $\text{Re}_D \approx 33\,000$, which puts the cylinders in the subcritical regime according to Williamson [49]. A rough estimation of the

cylinder drag coefficient using wake momentum deficit integration gave values around 1.2, which quantitatively confirms that the cylinders are in the subcritical regime (e.g., Refs. [2–4]). However, the authors note that investigation into the drag coefficient is outside the scope of the present study as the flow fields captured do not contain the entire wake for the full extent in the streamwise direction. Rough estimations of the drag coefficient was only made for the purpose of identifying the flow regime.

The flow fields were measured using 2D planar particle image velocimetry (PIV). The measurement plane was positioned just behind the end of the cylinders, in the x_1 - x_2 plane, at the center of the test section in x_3 . The origin of the measurement plane is placed at the center of the cylinders. The cylinders were deliberately placed outside of the field of view to avoid laser reflections from the cylinder saturating and damaging the camera sensors. Di-ethyl-hexyl-sebacate was aerosolized and injected as PIV seeding at the end of the test section. From there, it circulated throughout the entire closed-loop facility. The illumination was provided by two dual-pulse Litron Nano L Nd:YAG lasers emitting at 532 nm with a maximum energy of 200 mJ per pulse from each laser. The lasers were placed sequentially in the streamwise direction and synchronized to provide a single elongated sheet. Two LaVision Imager MX 25 MP cameras with Zeiss 100-mm lenses flanked two LaVision Imager LX 16 MP cameras with Nikon 200-mm lenses to capture the PIV images. The four cameras were placed sequentially in the streamwise direction to capture a rectangular field of view (FOV) that measures $0.965 \text{ m} \times 0.280 \text{ m}$, or $19.3D \times 5.6D$. Relative to the position of the cylinder, the FOV covers $0.7 \leq x_1/D \leq 20$ and $-2.8 \leq x_2/D \leq +2.8$. Extreme care was used in the alignment and synchronization of this system; note this same experimental setup was used for the acquisition in other studies as well e.g., Ref. [56]). Stitching between the vector fields was done through a hybrid weighting function that combines linear and error functions in the overlapping regions, which accounts for more than 10% of the individual camera FOV. This type of stitching is also used by Li *et al.* [37] for their PIV fields. Note that the total FOV size presented here is cropped, as the two types of cameras have different image sizes and cropping is needed to create a rectangular FOV. Figure 1 provides a schematic of the setup of the cylinders inside the test section, as well as the PIV setup. A total of 2000 image pairs were acquired at 1.5 Hz for each test case. At this acquisition frequency, there are approximately seven flow-throughs of the entire FOV between subsequent vector fields, ensuring that each field is independent. Postprocessing of the PIV images was done with DaVis 10.1 to produce velocity vector fields. Multipass image correlation was employed, starting with an initial pass with a 96×96 window and ending with a final pass with a 48×48 window with 75% overlap. This resulted in a 480×1364 instantaneous vector field for each image pair with a vector spacing of 0.72 mm. The uncertainty in the velocity fields estimated by DaVis is approximately 1.5 %; uncertainties were calculated based on the PIV correlations [57,58].

B. Background flow characterization

Table II shows the mean flow and turbulence characteristics of the four inflow conditions. The four test cases are denoted by the case names REF, FST8, FST12, and FST14, where FST indicates freestream turbulence generated by the active grid and the subsequent numbers represent the freestream turbulence intensity in percentage rounded to the nearest integer. The Taylor microscale, λ , is calculated by assuming isotropy at the small scales, viz. $\lambda^2 = 15\nu\overline{u_1'^2}/\epsilon$, where $\epsilon = 15\nu(\partial u_1'/\partial x_1)^2$ is the turbulence dissipation rate. We will later show that the isotropy assumption is valid through examination of the PIV results.

The separation of scales in the generated turbulence can be seen in Table II, as well as in the spectra presented in Fig. 2. The difference between the integral scale L_{11} and the Kolmogorov scale η increases as FST increases. In practice, this means that by changing our grid modes in this way, we are in fact increasing Re_λ . As such, the integral scale increases, the turbulence intensity increases, and the Kolmogorov scale decreases. Thus, “increasing FST” should be interpreted in this way, i.e., the scale (separation of scales and intensity) of the turbulence increases. Active grids have also been used in other novel ways where some of the turbulence properties, such as turbulence intensity and

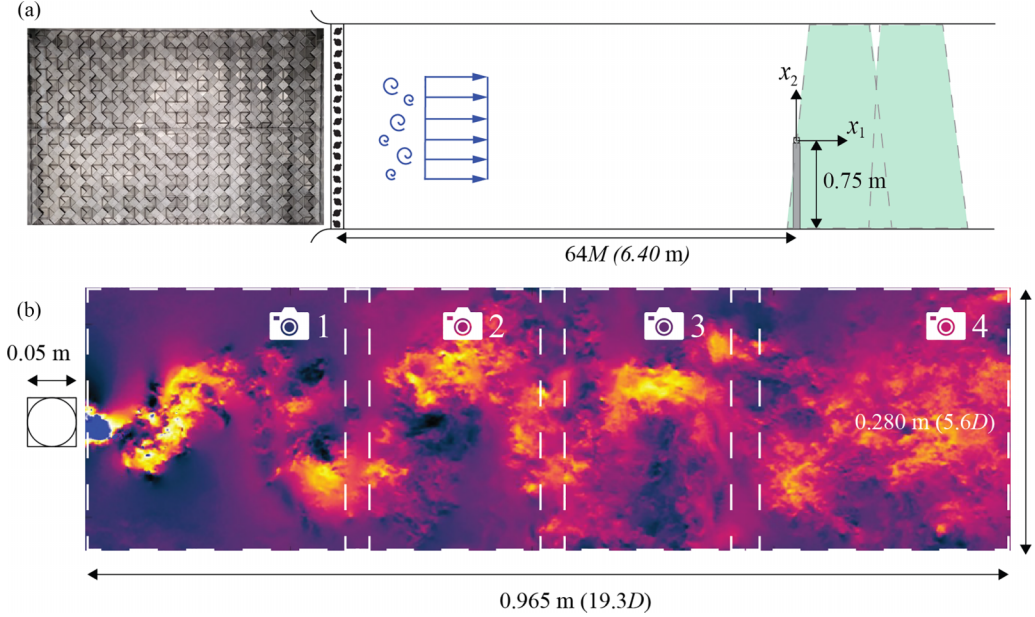


FIG. 1. Schematics of the setup of (a) the cylinders in the wind tunnel with the active grid shown at the inlet and (b) the PIV lasers and cameras system. The size and location of the cylinders in (a) are to scale with respect to the cross-sectional plane of the test section. The PIV setup in (b) is also to scale in terms of the size and position of the cylinders relative to the FOV.

integral length scale, can be independently varied. This can be done through changing the wing geometry (e.g., Refs. [29,59]) or through independent control of each wing [60]. However, these methods are outside the scope of this study and therefore not incorporated here.

In addition to the hot-wire characterization of the inflow, PIV measurements of the background flow were also conducted with the cylinders removed. To check the quality of the PIV measurements, we computed the u'_1 spectra based on the instantaneous velocity fields for the three turbulent cases and compared them to the spectra measured by the hot-wire. This is shown in Fig. 2 and the spectra collapse well. Furthermore, the spectra computed from the PIV data extend into the dissipation range, showing that the spatial resolution of the PIV data is sufficiently fine to resolve

TABLE II. Turbulence statistics of the incoming flow measured at the leading edge of the cylinders in the empty test section. The global isotropy ratio, $\overline{u'_1/u'_2}$, is calculated from the spatial average of the background flow field obtained through PIV.

Case name		REF	FST8	FST12	FST14
$\Omega \pm \omega$	(Hz $\pm$ Hz)	–	5 ± 2.5^a	2 ± 1	1 ± 0.5
U_∞	(ms ⁻¹)	10.5	10.6	10.6	10.8
u'_1/U_∞	(%)	1.1	7.5	12.1	13.8
u'_1/u'_2		0.79	1.10	1.01	1.10
L_{11}/D		5.12	4.33	5.68	7.86
η/D	(10 ⁻³)	13.41	4.84	3.56	3.44
Re_λ		70	544	755	958
Re_D		32 600	32 700	32 600	33 100

^aIndicates that FST8 only actuated the vertical wings.

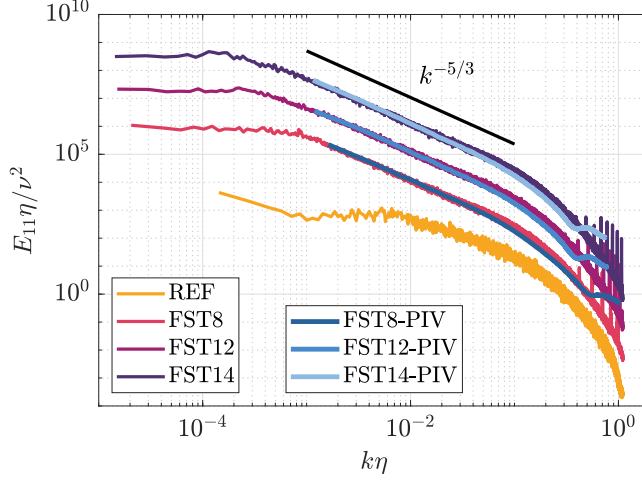


FIG. 2. Power spectral density of the streamwise velocity fluctuations for all the inflow cases, each offset by a decade for clarity. The spectra calculated from the PIV images for the three turbulent cases are overlaid for comparison.

flow structures smaller than λ . This agreement between hot-wire and PIV is exceptional and far exceeds what is traditionally achievable; this is a result of the high resolution of the cameras (allowing access to the small scales/high wave numbers) and the large field of view (enabling access to lower wave numbers).

Figure 3 presents the streamwise profiles of U_1/U_∞ , U_2/U_∞ , turbulence intensity, and isotropy for all four inflow conditions. Each data point along the x_1 direction represents an average of the corresponding mean fields along the x_2 direction. The error bars indicate the RMS variation in the x_2 direction. To reduce clutter, only every 30th data point is plotted. The turbulence intensity and isotropy profiles exclude case REF, which serves as a reference case with no deliberately added freestream turbulence. Additionally, light blue curves are overlaid on the turbulence intensity profiles to illustrate a power-law decay relation of x_1^{-1} for comparison.

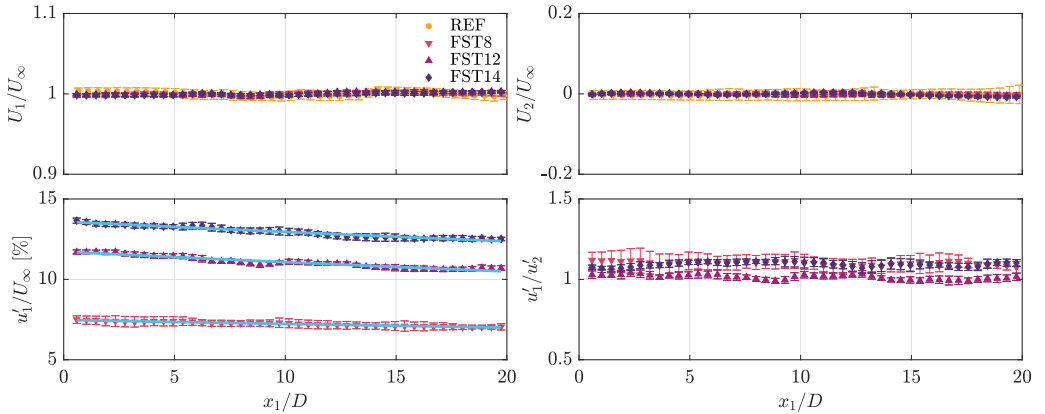
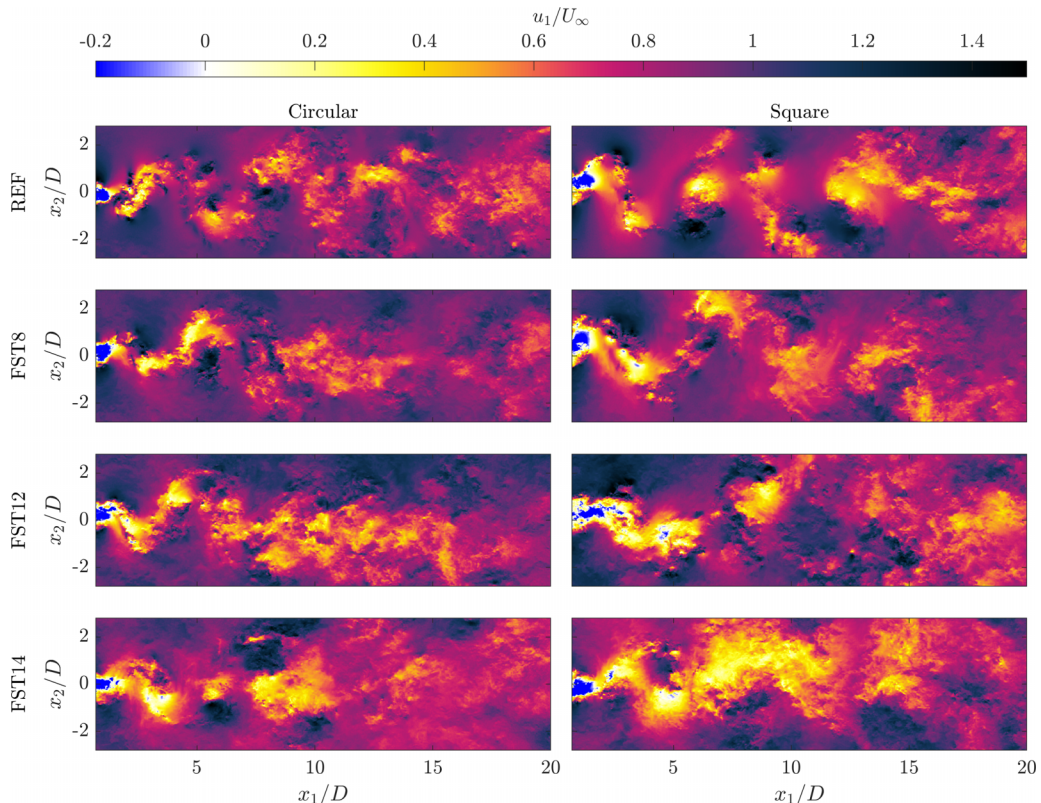


FIG. 3. Time-averaged streamwise profiles of U_1/U_∞ , U_2/U_∞ , u'_1/U_∞ , and u'_1/u'_2 of the background flow without the cylinders. The light blue curves indicate a reference power-law decay, $u'_1 \propto x_1^{-1}$. The error bars indicate the RMS variations in the x_2 direction.

FIG. 4. Example instantaneous u_1/U_∞ fields of all eight test cases.

The velocity components U_1 and U_2 remain relatively constant throughout the investigated range, with the variation in U_1 along the x_2 direction being within 1%. This variation falls within the accuracy range of the PIV measurements. The turbulence intensities for all cases exhibit consistency with a power-law decay, with maximum variations of approximately 0.3% along the x_2 direction. The isotropy profiles for the turbulent cases indicate that all cases exhibit a low degree of anisotropy, with values ranging from 0.99 to 1.11 throughout the investigated range. Based on these profiles, we can conclude that the turbulent flow fields within the measurement field of view can be considered as approximately homogeneous and isotropic turbulence, whereby homogeneity is used to specifically refer to the transverse planes. As our flows are shown to be homogeneous and isotropic at the large scales, it follows that the flows are also homogeneous and isotropic at the small scales, thereby justifying our earlier calculations of λ through the isotropic assumption.

III. THE MEAN FIELD

Figure 4 displays example instantaneous u_1/U_∞ fields for all eight cases. Qualitatively, these visualizations provide insight into the effects of freestream turbulence on the wake behind the cylinders. In the two REF cases, coherent structures can be observed in the wake, indicative of von Kármán vortex streets that extend for the majority of the velocity field. As the level of freestream turbulence increases, these coherent structures begin to break down closer to the cylinder. This trend continues until we reach the FST14 cases for both cylinders, where distinct evidence of vortex shedding is only visible in the first half of the field, up to $x_1/D \approx 10$. Qualitatively speaking, this breakdown of coherent structures is due to the enhanced momentum mixing in the wake with the

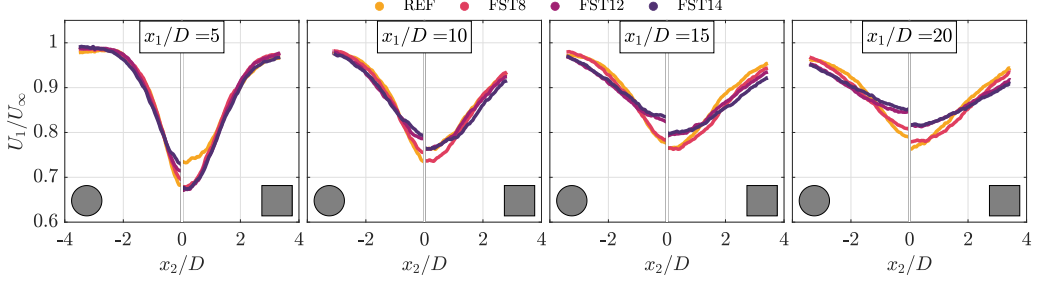


FIG. 5. Transverse profiles of U_1/U_∞ for all test cases at $x_1/D = 5, 10, 15$, and 20 . Only half of each profile is plotted due to symmetry about the wake centerline.

freestream when FST is added (e.g., Ref. [31]). This in turn leads to promoted formation of 3D structures, as seen in a separated boundary layer [61]. This is analogous to the formation of 3D structures in a cylinder wake when Re_D is increased [44]. These 3D structures work together with the FST to enhance the momentum flux in the wake. In a time-averaged sense, enhanced flux leads to a wider wake (e.g., Refs. [17,23]) and faster wake velocity deficit recovery in the intermediate-wake region e.g., Refs. [23,26–30]). For the purpose of this study, the near wake is defined as $x_1/D < 3$, while the intermediate wake is defined as $3 \leq x_1/D \leq 20$.

Figure 5 presents the time-averaged normalized U_1 velocity profiles for both cylinder geometries across all inflow conditions. Due to the symmetry of the profiles about the wake centerline ($x_2 = 0$), only half of each profile is shown. Drawings of the cylinder shape indicate the corresponding profile in the plots. The profiles are shown at selected streamwise positions of $x_1/D = 5, 10, 15$, and 20 . It is evident that as FST increases, we see both a reduction in the centerline velocity deficit $U_S(x_1)$ and an increase in the wake width for both cylinders. This is in agreement with Eames *et al.* [23]. It is also evident that the square cylinder generally exhibits a larger velocity deficit and a wider wake than the circular cylinder. One thing to note for the square cylinder is that when FST is added, there is a significant increase in the velocity deficit at $x_1/D = 5$. This is associated with a lengthening of the recirculation region immediately behind the cylinder, as will be shown later. As we move downstream for both the circular and square cylinders, it becomes apparent that the influence of the four inflow cases can be placed into two distinct groups. For both cylinder geometries, the velocity profiles for cases REF and FST8 exhibit similarities, while those for cases FST12 and FST14 form another distinct grouping. This grouping becomes visible at least from $x_1/D = 10$. One possible explanation for this behavior is that a certain threshold of freestream turbulence intensity needs to be achieved before a significant influence on the mean wake velocity can be observed. We note here that, compared to the literature, our inflow conditions mark some of the highest freestream turbulence level achieved while maintaining very close approximations to homogeneous and isotropic turbulence.

The wake geometry evolution can be better examined by looking into the variations of the centerline velocity deficit, U_S , and the wake half-width, ℓ , as the wake evolves in the x_1 direction; this is shown in Fig. 6. In the near wake ($x_1/D < 3$), we see different behavior between the two cylinders. While the circular cylinder remains relatively unaffected by the FST in terms of U_S and ℓ , the square cylinder exhibits significant lengthening of the recirculation region, identified by $U_S > 1$. This is perhaps counterintuitive as the separation point on a circular cylinder is dependent upon the boundary layer state, whereas on a square cylinder, the separation point is typically fixed at the corners. However, elevated FST can lead to the reattachment of the separated shear layer on a square cylinder (e.g., Ref. [19]), which in turn leads to a lengthening of the recirculation region due to secondary separation at the leeward corners, as was found by Li *et al.* [22]. Similar effects have been observed for the reattachment location of the separated boundary layer on a thick flat plate by Saathoff and Melbourne [62]. Parallels can be drawn with a similar effect for rectangular cylinders

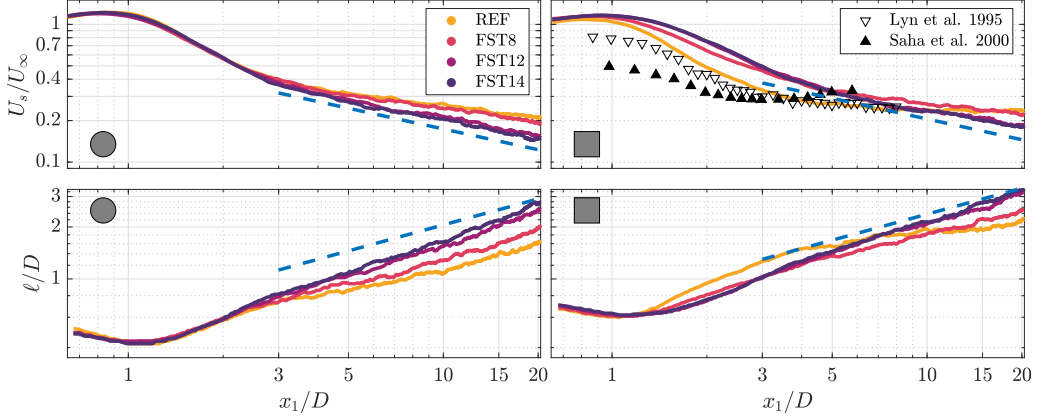


FIG. 6. The streamwise profiles for the normalized wake centerline velocity deficit U_s/U_∞ (top row) and the normalized wake half-width ℓ/D (bottom row) for all the test cases. The light blue dotted lines represent the analytical power-law relations in the self-similar region (p. 148 in Ref. [24]).

with high aspect ratios, where the separated boundary layer reattaches simply due to the elongated cylinder geometry. This can be observed in the summary of numerical studies of flow around a 5:1 rectangular cylinder by Bruno *et al.* [63], across a wide range of Re_D in the subcritical to critical regimes. This reattachment can explain our observations of the recirculation region behavior for the square cylinder. As for the circular cylinder, since we are still in the subcritical regime for all the test cases (based on an estimation of $C_D \sim 1.2$ for all the cases), the separation point of the boundary layer is not expected to change significantly, which leads to an insensitivity of the recirculation region behind the circular cylinder to the influence from FST.

Beyond $x_1/D = 3$, differences in the U_s and ℓ behavior start to emerge. For both cylinder geometries, the decay rate for U_s and the expansion rate for ℓ increases with elevated FST. We have superimposed the canonical power laws $U_s \sim x_1^{-1/2}$ and $\ell \sim x_1^{1/2}$, expected in the self-similar region of the wake, as dotted blue lines for reference in Fig. 6. We observe that for the circular cylinder, both U_s and ℓ follow power-law behavior in x_1 starting from $x_1/D \approx 3$ and that the power-law relations become more similar to the self-similar solutions as FST increases. The same behavior is also seen for the square cylinder. This indicates that elevated FST, at least within the range tested in this study, promotes self-similarity in the wake earlier than traditionally expected. Here we want to state that we are not explicitly calling the wake self-similar but rather commenting that FST is causing the wake to trend towards self-similarity in a shorter distance than canonically expected, as $20D$ is not typically considered to be in the far wake [51]. In addition, we have overlaid the results from Lyn *et al.* [42] and Saha *et al.* [43] for U_s behind a square cylinder in quasilaminar flow as canonical comparisons against our results, which broadly follow the same trend. The wake of the square cylinder is also wider than that of the circular cylinder, as can be seen by comparing the wake half-width values. The velocity deficit is also higher for the square cylinder. We saw these qualitatively already in the transverse U_1 profiles shown in Fig. 5, but this is more explicit here. Lastly, the grouping of behavior observed in Fig. 5 becomes more apparent for both cylinder geometries here. For the circular cylinder, the $U_s(x_1)/U_\infty$ profiles start to split into two groups from $x_1/D \approx 5$, with cases REF and FST8 forming one group, and cases FST12 and FST14 forming the other.

It is important to note that for case FST14, the integral length scale L_{11}/D is 7.86, which is greater than the same ratio in the study by Eames *et al.* [23] (approximately 6.8). Eames *et al.* [23] observed that for the largest L_{11} in their study, U_s and ℓ vary as x_1^{-1} and x_1^1 , respectively. However, in the present study, even for the highest L_{11}/D ratio, U_s and ℓ exhibit behavior close to

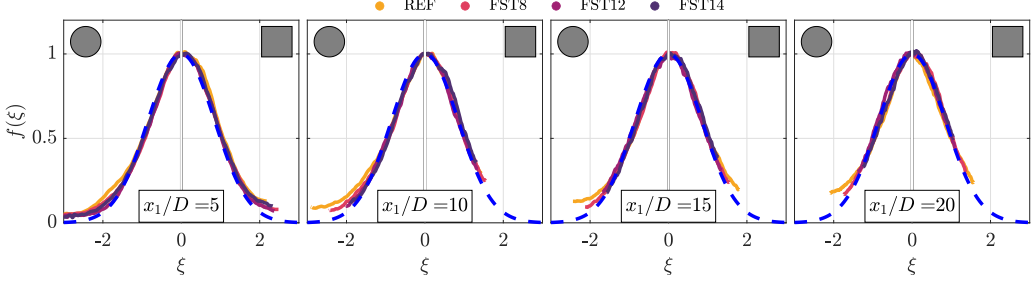


FIG. 7. Normalized streamwise velocity deficit profiles f as a function of $\xi = x_2/\ell$ for all the cases for $x_1/D = 5, 10, 15$, and 20 . The blue dotted curves represent the analytical solution of $f(\xi) = \exp(-\alpha\xi^2)$, where $\alpha = \ln(2)$, expected in the self-similar region (p. 149 in Ref. [24]). Only half profiles are plotted for each case due to their symmetrical nature.

the canonical power-law relations within the measurement region, which is $U_S \propto x_1^{-1/2}$ and $\ell \propto x_1^{1/2}$ (p. 148 in Ref. [24]). This discrepancy can be explained by two factors. First, the Reynolds number in the present study is an order of magnitude higher. Previous studies have shown that the vortex formation in the wake of a cylinder changes significantly with Reynolds number in the range of $Re_D \sim O(10^3)$ to $O(10^4)$, and the addition of freestream turbulence further modifies the flow in the wake [13,40]. Thus, the rapid spatial development observed by Eames *et al.* [23] may partially be a Reynolds number effect. Second, the transverse flow homogeneity should be considered. The profiles for u'_i/U_∞ in the x_2/D direction in Eames *et al.* [23] vary by up to 5% in absolute value, which is an order of magnitude greater than the variation observed in the present study. It is known that three-dimensional effects in the shear layer roll up in the near wake of a cylinder starts to appear at Re_D near $O(10^3)$ due to the distortion and breakdown of secondary vortices in the shear layer [64–66]. The inhomogeneity in the incoming flow, coupled with three-dimensional effects in the shear layer, could have caused the deviations from canonical behavior reported by Eames *et al.* [23].

In Fig. 7, the normalized velocity deficit profiles in self-similar variables $f(\xi)$ are shown for all inflow cases of the circular and square cylinders. Again, we show half profiles for each case because of symmetry. Here $\xi = x_2/\ell$ and $f(\xi) = (U_\infty - U_1(x_1, x_2))/U_S(x_1)$. The profiles exhibit good agreement with the analytical solution for $-1 \leq \xi \leq +1$, regardless of the inflow condition or cylinder geometry. This demonstrates a certain degree of robustness of the mean wake velocity to the initial conditions. Beyond $|\xi| \geq 1$ towards the tail of the $f(\xi)$ profiles, case REF for the circular cylinder deviates noticeably from the analytical solution at all four x_1/D locations. The deviation does not decrease in magnitude even at $x_1/D = 20$, indicating that the wake of the circular cylinder does not reach a self-similar state within the investigated flow field for the least turbulent inflow (REF). This is not surprising as one would typically not expect to have achieved self-similarity this close to the cylinder in the canonical (laminar) inflow case. In contrast, when the freestream turbulence is elevated, a steady approach to the analytical solution is observed downstream in the wake. The same can be observed for the square cylinder, although the differences between case REF and the other cases are less pronounced. This again shows that elevated FST promotes a more rapid approach to self-similarity.

Overall, it is observed that the wake behind a cylinder, influenced by freestream turbulence, behaves differently depending on the cylinder geometry. In the near-wake region, freestream turbulence has no noticeable impact on the size and shape of the recirculation region immediately behind the circular cylinder, in contrast with the square cylinder. This difference could be attributed to the freestream turbulence having a greater effect on the separation and reattachment of the boundary layer on a square cylinder compared to a circular cylinder due to the subcritical nature of the flow past the cylinders. Moving farther downstream, elevated freestream turbulence changes the decay

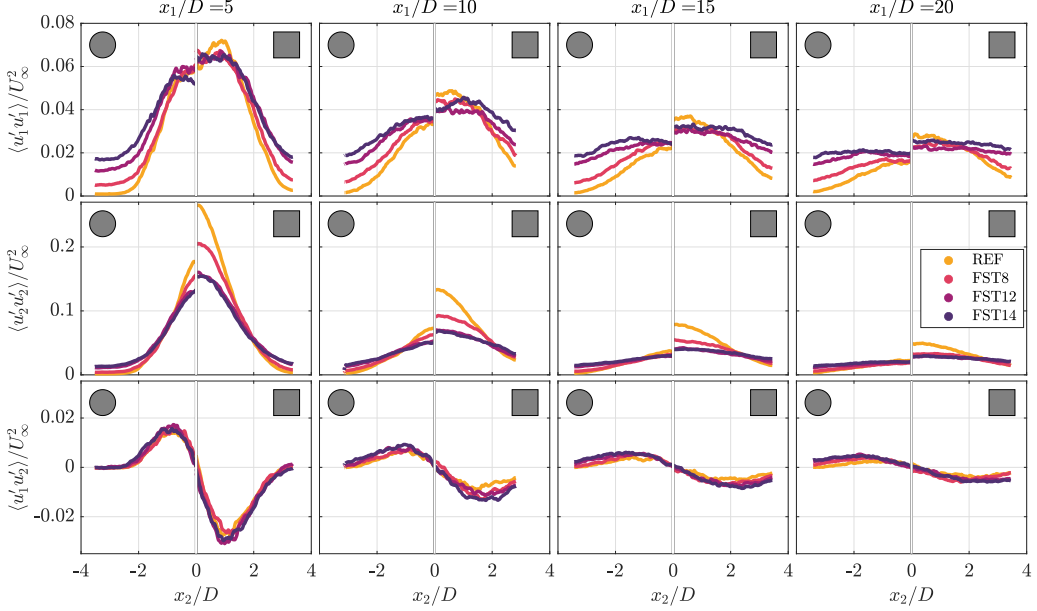


FIG. 8. Time-averaged transverse Reynolds stress profiles for all cases at $x_1/D = 5, 10, 15$, and 20 , showing $\langle u'_1 u'_1 \rangle$, $\langle u'_2 u'_2 \rangle$, and $\langle u'_1 u'_2 \rangle$. Only half profiles for each case are shown due to symmetry; all profiles are normalized by U_∞^2 .

rate of U_S and the expansion rate of ℓ to be closer to the expected analytical values in the self-similar region, indicating a promotion toward self-similar behavior in the mean wake velocity profile, and this trend appears to be monotonic up to the highest tested freestream turbulence intensity of 13.8%.

IV. THE REYNOLDS STRESSES

In Fig. 8, the normalized Reynolds stresses are shown for all test cases. Focusing first on $\langle u'_1 u'_1 \rangle$, we see that FST augments the streamwise velocity fluctuations more significantly near the edges of the wake compared to the center, as indicated by the profiles diverging from each other as $|x_2/D|$ increases. This is evident for both cylinder geometries. We also see that the streamwise velocity fluctuations are more intense in the wake of the square cylinder than the circular cylinder. The wider nature of the square cylinder wake can be seen by the fact that the circular cylinder's velocity fluctuations return, more or less, to the freestream level at the edge of the FOV, even at $x_1/D = 20$, while the square cylinder shows much higher fluctuations at the edge even at $x_1/D = 10$. Case REF for the square cylinder shows remnants of the twin peak feature associated with the separated shear layer, at $x_1/D = 5$. This feature is not distinctly observed for the circular cylinder. This demonstrates that the square cylinder has stronger separated shear layers. Lastly, the peak near the wake center for the square cylinder is attenuated by the presence of FST. The same is not observed for the circular cylinder. The attenuation is an indication of a disruption of the vortex shedding process, which will be discussed more in combination with $\langle u'_2 u'_2 \rangle$.

Looking at the transverse velocity variance $\langle u'_2 u'_2 \rangle$, we first observe that the fluctuations for the square cylinder are higher. This is consistent with the comparison of $\langle u'_2 u'_2 \rangle$ between a square [42,67] and a circular [68,69] cylinder found in the literature. There is also significant attenuation by the addition of FST, which is especially evident for the square cylinder, where at $x_1/D = 5$, the central normalized peak value reduces from 0.27 to 0.15 from case REF to case FST14, a reduction of 44%. Subsequent streamwise positions shows similar percentage reduction between these two cases (between 40% and 50%). It is apparent that the near-wake attenuation of the transverse Reynolds

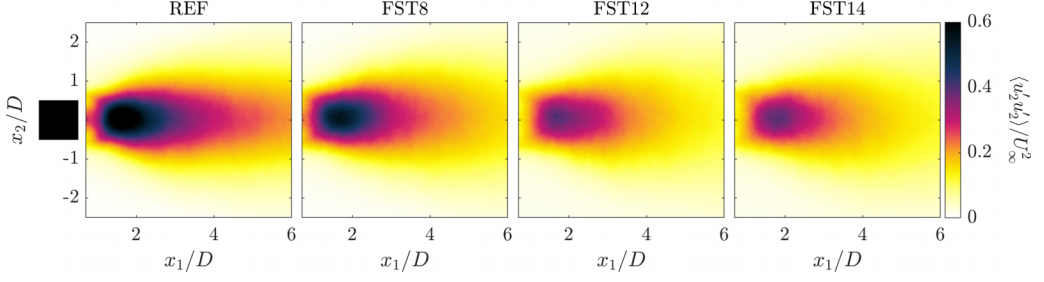


FIG. 9. Time-averaged $\langle u'_2 u'_2 \rangle / U_\infty^2$ fields in the near wake for the square cylinder cases.

normal stress observed by Li *et al.* [22] for the wake of a square cylinder subjected to FST extends into the intermediate-wake region. The circular cylinder also shows attenuation of $\langle u'_2 u'_2 \rangle$ by FST, but to a much lesser extent. This is related to the relative lack of influence that FST has on the recirculation region and vortex formation region behind the circular cylinder for the present study, which has been a theme throughout.

The Reynolds shear stress, $\langle u'_1 u'_2 \rangle$, does not appear to be significantly influenced by the addition of freestream turbulence in the intermediate wake. This is expected because in a nearly homogeneous and isotropic turbulent freestream flow, the Reynolds shear stress is negligible due to the absence of both shear and production of turbulent kinetic energy, i.e., $\langle u'_1 u'_2 \rangle \approx 0$ [32,34]. Therefore, any generation of Reynolds shear stress can only come from the wake of the cylinder itself. As a result, all the profiles appear similar to each other regardless of the inflow conditions. We make a passing note that in the near wake, there are differences in the Reynolds shear stress profiles between the cases. These differences, however, diminish quickly as we move downstream, as shown by Li *et al.* [22].

In addition to examining the behavior of Reynolds stresses in the intermediate wake, it is also interesting to explore the near-wake region immediately behind the cylinders. In Fig. 9, we observe that, for the square cylinder, the $\langle u'_2 u'_2 \rangle$ field is highly influenced by the freestream turbulence, already seen in the intermediate wake and also consistent with the findings of Li *et al.* [22]. Clear regions of high transverse velocity fluctuations form toward the end of the recirculation regions, reaching a peak along the centerline at approximately $x_2/D = 2$. As shown by Li *et al.* [22], these regions of transverse velocity fluctuations are associated with vortex shedding, and elevated freestream turbulence weakens this process, especially when the freestream turbulence contains large integral scales. Moreover, the largest integral scales present in the work of Li *et al.* [22] is under $2D$, whereas the present work has much larger scales ($\sim 8D$). Therefore, we would expect even greater attenuation of the near-wake transverse velocity fluctuations due to FST in our cases compared to Li *et al.* [22]. The attenuation effect is significantly less pronounced for the circular cylinder (not shown). For $\langle u'_1 u'_1 \rangle$ in the near field, the effects of both FST and cylinder geometry are less pronounced, and thus we do not show them here for brevity.

In summary, we observe that freestream turbulence has varying effects on the different components of the Reynolds stresses. In the intermediate wake between $x_1/D = 5$ and $x_1/D = 20$, increasing the freestream turbulence generally leads to an increase in $\langle u'_1 u'_1 \rangle$ along the centerline but a decrease in $\langle u'_2 u'_2 \rangle$. The Reynolds shear stress $\langle u'_1 u'_2 \rangle$ is not significantly affected since the incoming turbulence is nearly homogeneous and isotropic. This is consistent in principle with the findings of Matsumura and Antonia [41], Yiu *et al.* [44], Chen and Buxton [46], where they saw that the Reynolds shear stress profiles in the intermediate wake are not significantly influenced by the inflow conditions if $\langle u'_1 u'_2 \rangle \approx 0$ in the freestream. Although we note here that their inflow conditions differ by Re_D , whereas ours differ by FST. In the near wake immediately behind the cylinder, the Reynolds stress components exhibit different behavior. While the $\langle u'_1 u'_1 \rangle$ fields in the separated shear layer remain relatively similar across the different inflow cases, the $\langle u'_2 u'_2 \rangle$ fields behind the

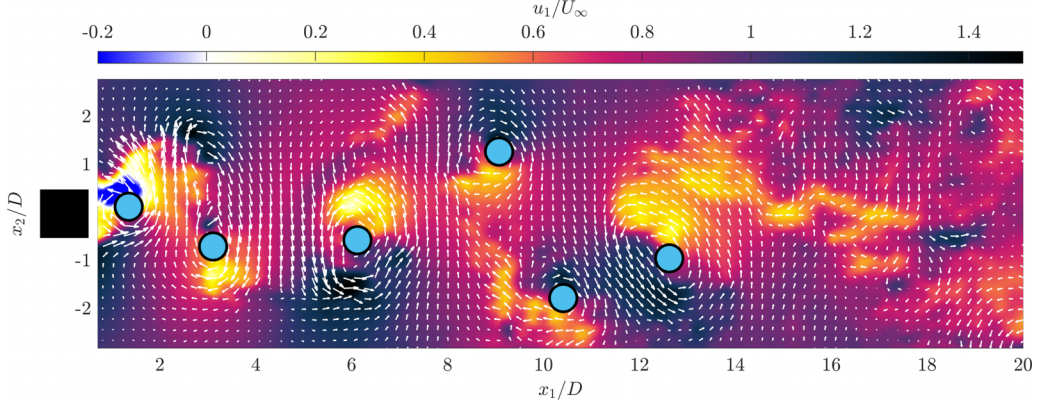


FIG. 10. Example of vortices detected based on the method of Graftieaux *et al.* [70] for an instantaneous PIV snapshot for the square cylinder for case REF. The contours show u_1/U_∞ and the mean subtracted velocity fluctuations are depicted by the vectors. The blue dots are the detected vortex centers. Every 15th vector is plotted to reduce clutter.

recirculation zone show significant attenuation with increasing freestream turbulence, especially for the square cylinder.

V. VORTICES IN THE WAKE

The vortex detection method proposed by Graftieaux *et al.* [70] is utilized to quantify the average number of vortices present in the wake for all test cases. In brief, this method calculates the sum of the cross product of the instantaneous velocity fluctuation field with a spatial array of radial distance away from a point P . If the velocity vectors are rotating about the point, indicating the presence of a vortex, then the sum at that point will be elevated. The spatial array is set to be 107×107 vectors in size, which was optimized for detecting coherent vortex shedding from the cylinders while avoiding the smaller vortices associated with turbulence. A sensitivity analysis was performed by varying the array size from 35 to 125 vectors. For array sizes greater than 53×53 vectors, the mean vortex count for both cylinders exhibit the same trend. Prior to the computation, the velocity fluctuation field is smoothed by a filter with square window size corresponding to the Taylor microscale λ for each case. Figure 10 shows an example instantaneous PIV snapshot of the square cylinder for case REF with detected vortex centers overlaid on top of the u_1/U_∞ field and the velocity fluctuation vectors.

Figure 11(a) illustrates the average number of vortices detected in the wake across all 2000 instantaneous fields for each test case. The results reveal a monotonic decrease in the average vortex count with increasing FST for both the circular and square cylinders. Specifically, the average vortex count reduces by approximately 40% for the circular cylinder and 38% for the square cylinder as the FST increases from 1.1% to 13.8%. Furthermore, the average number of vortices detected for the two cylinders are very similar to each other for all inflow cases, and they become more similar as FST increases. Thus, the differences observed here between the two cylinders are small and within their respective uncertainties, and it is the overall global trend of decreasing vortex counts with increasing FST that should be the main focus.

To gain further insight into the effect of freestream turbulence on the vortices in the wake, the distribution of vortex counts is examined. Figure 11(b) presents the probability density function of vortex counts for all test cases and both cylinder geometries. The shifting of the peak and the changes in the skewness of the distributions contribute to the observed decrease in the mean number of vortices. As the freestream turbulence intensity increases, several notable changes in the distribution

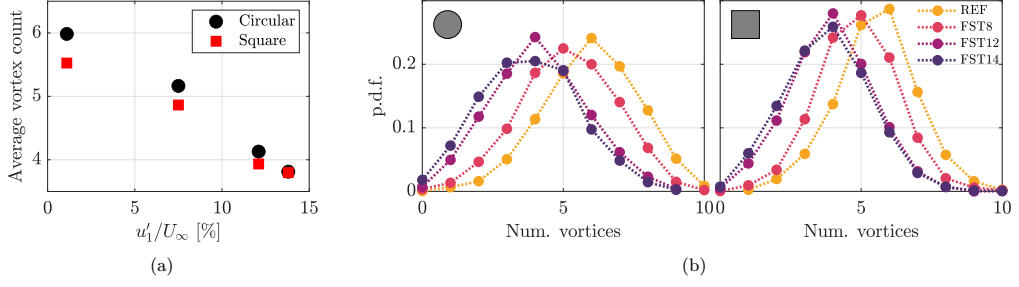


FIG. 11. (a) Average number of identifiable vortices relative to the incoming freestream turbulence intensity for the circular and the square cylinders; (b) probability density functions of the number of identifiable vortices in the cylinder wake.

of vortex counts become apparent. First, the peak of the distribution shifts towards the left, indicating a reduction in the number of vortices. Second, the distributions become more skewed to values nearer zero and are no longer symmetric. In essence, the distributions exhibit a “shift” towards zero as the level of freestream turbulence increases. This trend implies that the presence of higher freestream turbulence intensity has a suppressive effect on the overall number of large coherent vortices detectable in the wake.

The decrease in the average number of vortices in the wake as FST increases is not due to a breakdown of the initial vortex formation process. Figure 12 displays the time-averaged vorticity fields, $\Omega_3 = \partial U_2 / \partial x_1 - \partial U_1 / \partial x_2$, in the near wake for all the cases. The size, shape, and magnitude of the vortex formation regions do not exhibit significant changes with increasing freestream turbulence. The largest change observed is for the square cylinder when FST is added, where we see a slight spread in the regions of large magnitude of Ω_3 . However, the changes are small. Moreover, the differences between the Ω_3 fields of FST8, FST12, and FST14 are negligible. These findings indicate that freestream turbulence does not notably alter the vortex formation process in the near wake behind a cylinder, and the decreasing number of coherent vortices in the wake as FST increases is purely due to enhanced mixing and vortex breakdowns caused by turbulence.

Overall, increasing freestream turbulence affects mostly how vortices in the wake propagate and not how they form. The near-wake time-averaged vorticity fields show no discernible effects from

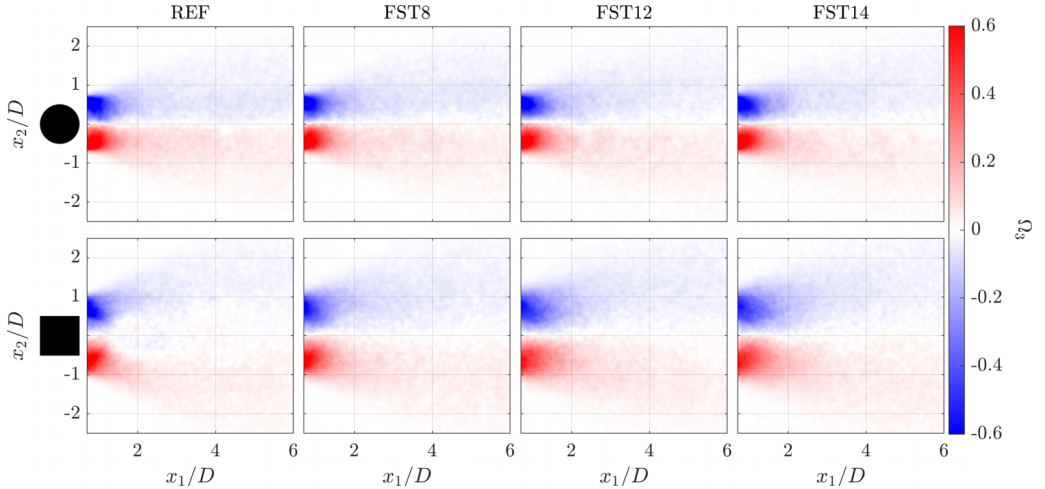


FIG. 12. Time-averaged vorticity fields in the near wake for all test cases.

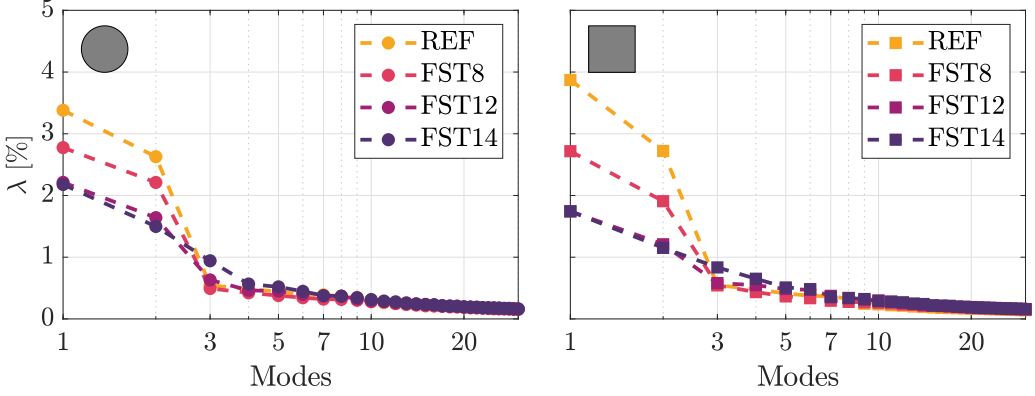


FIG. 13. Ordered energy content λ of the first 30 ω_3 POD modes for the circular cylinder (left) and the square cylinder (right).

freestream turbulence, while in the intermediate wake, the von Kármán vortex streets are dispersed and shortened by increasing FST. The average number of vortices correspondingly decreases in the wake.

VI. PROPER ORTHOGONAL DECOMPOSITION

Proper orthogonal decomposition (POD) is a method used to analyze and decompose vector fields into spatial modes that capture the dominant flow structures. In this study, the snapshot POD method proposed by Sirovich [71] is applied to the vorticity fields ω_3 . The procedure decomposes each ω_3 snapshot into a linear combination of POD modes ϕ^i . Each mode has a corresponding modal energy λ_i , which can be ordered such that the first mode contains the most energy. The POD coefficients a_i^n can be computed to reconstruct the n th instantaneous ω_3 field using a linear combination of the POD modes, *viz.* $\omega_3^n = \sum_{i=1}^N a_i^n \phi^i$. Here all 2000 instantaneous vorticity snapshots are used to compute the first 1000 POD modes. However, for the subsequent analysis, we will only look at the energy content of the first 30 modes, and the mode shapes of the first four modes. These modes are the dominant ones that capture the most significant flow structures in the wake.

Figure 13 presents the energy content distribution (λ_i) of the first 30 POD modes for all cases. These modes capture approximately 12% of the total energy, with the first four modes accounting for 40% to 60% of that energy. Although this energy percentage is not nearly sufficient for a complete reconstruction of the vorticity field, these modes represent the most energetic patterns, particularly modes 1 and 2, which are associated with vortex shedding, as we will see later through the mode shapes. We can see that there is a monotonic decrease in the percentage energy contained in the first two modes as FST increases. The energy from modes 1 and 2 is redistributed to the subsequent modes, in particular modes 3 and 4, which contain more energy for cases FST12 and FST14 than for cases REF and FST8.

For the mode shapes, we examine the circular cylinder cases REF and FST14, as they are representative of the overall trend. In Fig. 14, we see that for the circular cylinder, the first two modes capture the von Kármán vortex street, as indicated by the distinct alternating regions of negative and positive values. Comparing cases REF and FST14, we see the effects of increasing FST emerge in two ways. First, the coherent nature of the mode shapes for modes 1 and 2 breaks down earlier when FST increases. For case REF, the structures in the first two modes remain distinguishable throughout the measurement domain, while for case FST14, the structures are smeared out by the presence of FST for $x_1/D \gtrsim 15$. Second, we observe some coherent structures in modes 3 and 4 for case REF, indicating that they are still primarily associated with the von Kármán vortex streets, while modes 3 and 4 for case FST14 are largely featureless except for the small region immediately behind the

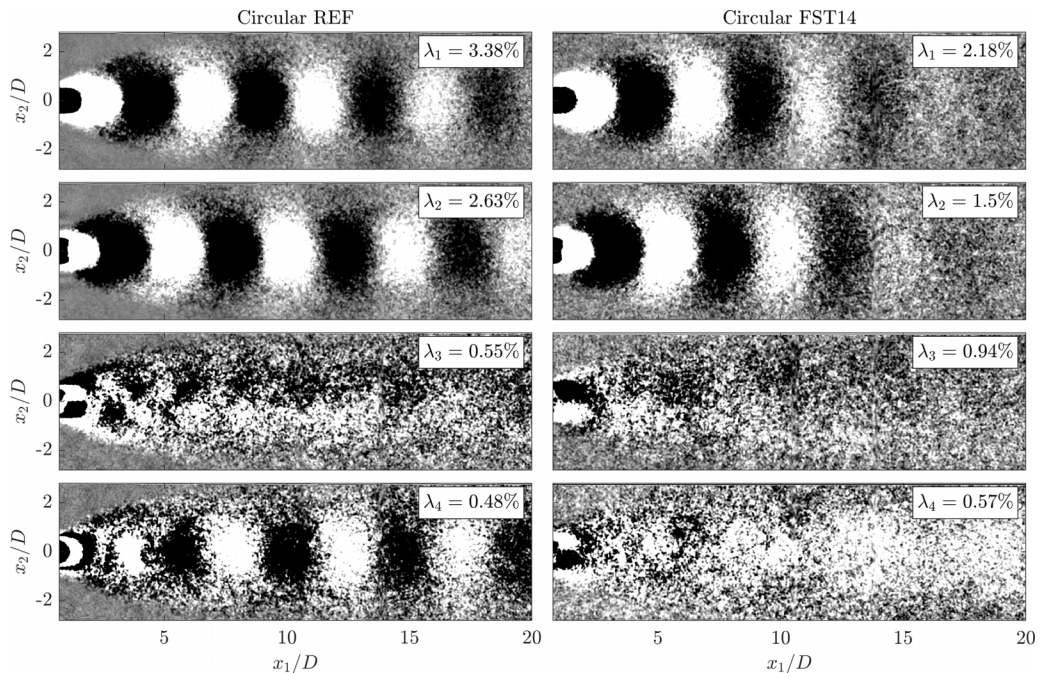


FIG. 14. Mode shapes ϕ^i for the first four modes for ω_3 . Only the least and the most turbulent inflow cases for the circular cylinder are shown. The white regions are positive, while the black regions are negative.

cylinder. The featureless modes for case FST14 are primarily associated with the turbulent flow in the wake, as there is no regular repeating spatial pattern in homogeneous, isotropic turbulence. Linking back to the energy content shown in Fig. 13, these modes are moved up in the hierarchy due to the presence of elevated FST, and supersede modes associated with vortex shedding. These trends correlate well with the decreased counts of coherent vortices detected in the wake as FST increases, and they are consistent with the findings of De Jesús *et al.* [31] that shows a breakdown of vortex periodicity caused by incoming turbulence.

In summary, the snapshot POD analysis reveals that the dominant mode of vorticity in the wake of a cylinder is associated with periodic coherent modes connected to vortex shedding even for freestream turbulence intensities up to 13.8%. However, the addition of freestream turbulence redistributes the energy associated with these vortex shedding modes to modes that are related to the background turbulent flow. For high turbulence intensities, the third and fourth most energetic mode shapes transition from being dominated by vortex shedding to being dominated by the background turbulence. For the first two modes, which are consistently associated with vortex shedding, the regular cell patterns observed in the mode shapes start to break down nearer the cylinder as freestream turbulence increases, correlating well with the decreased number of coherent vortices detected in the wake.

VII. CONCLUSIONS

The effect of freestream turbulence on the wake of circular and square cylinders was investigated using 2D planar PIV measurements. The study covered a large physical extent, with a FOV capturing approximately $19.3D \times 5.6D$ of the wake in a single instantaneous vector field. The experiments were conducted at a moderately high Reynolds number of $Re_D \approx 3.3 \times 10^4$, and four different inflow cases were generated, producing turbulence intensities ranging from 1.1% to 13.8% and different integral length scales L_{11}/D ranging from 4.32 to 7.86.

We find that, for both cylinder geometries, an increase in FST promotes the recovery of the centerline velocity deficit U_S and the expansion of the wake half-width ℓ . It also promotes early onset of self-similar behavior of the mean velocity profiles. Furthermore, the presence of FST significantly attenuates $\langle u'_2 u'_2 \rangle$ for the square cylinder and to a lesser degree for the circular cylinder. This is related to the weakening of the vortex shedding process. Last, vortex propagation in the wake is significantly affected by FST. While distinct vortices are observed up to $x_1/D \approx 15$ for the lowest FST case, the vortices break down earlier ($x_1/D \lesssim 10$) for the most turbulent case. This early breakdown results in a reduction of around 40% in the average number of coherent vortices in the wake. Snapshot POD analysis of the vorticity field reveals that elevated FST not only transfers energy from the two most energetic modes associated with vortex shedding to lower modes but also elevates modes associated with the background turbulent flow above some of the lower vortex shedding modes.

There are also some qualitative differences between the circular and the square cylinder wakes in their response to different incoming turbulence. In the near wake, the length of the recirculation region behind the circular cylinder is not significantly affected by different freestream turbulence levels, whereas for the square cylinder, the length increases as FST increases. In the intermediate wake, the wake is generally wider for the square cylinder.

These findings demonstrate that FST promotes an earlier onset of self-similarity in the wake of a cylinder. The consistent behavior observed for both circular and square cylinders suggests that the specific geometry that produces the wake becomes less important as FST increases. Furthermore, larger-scale FST leads to a faster breakdown of coherent vortices in the wake and a decrease in the average number of detected vortices. These findings are consistent with some earlier studies while contradicting others. In the present study, we have compared different types of cylinders, captured a large contiguous field of view, and pushed to higher Re_D and turbulence levels while maintaining HIT, enabling observations of the fundamental behavior closer to a Reynolds number independent state than previously observed.

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L.L. and R.J.H. conceived the idea; L.L. performed the experiments and the data analysis; L.L. is the primary author of the manuscript; all authors contributed to the writing and reviewing of the final manuscript.

The authors report no conflict of interest.

DATA AVAILABILITY

The data presented herein, including all instantaneous PIV fields, are available at [72].

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