

Wall-mounted finite cylinder wake structure modification due to boundary layer-wake interaction: Half-loop and full-loop coherent structure topologies

Z. Hosseini^a, J. A. Bourgeois^a, R. J. Martinuzzi^a

^a*University of Calgary, 2500 University Dr., Calgary, AB, Canada*

ABSTRACT: Earlier studies suggest that two types of shedding structures can be recognized in the wake of surface mounted cylinders. For height to width ratios lower than a critical limit, in the time averaged wake, a counter rotating vortex pair is present at the free-end. For taller cylinders another counter rotating pair is also noticed at the cylinder base. While some differences in the shedding process are discussed; due to insufficiently resolved data in spatial domain a detailed comparison of the three-dimensional turbulent field is not well documented. In addition to height to width ratio, boundary layer thickness can also change the wake structure; its effects, however, are not examined thoroughly. This work shows that the boundary layer has a key role on the shedding process. It is shown that even for a rather tall cylinder (significantly taller than the critical limit suggested in earlier work) both types of wakes can be observed depending on the boundary layer thickness. The three-dimensional phase averaged flow is reconstructed from planar PIV measurements and comparisons of the mean and dynamic wake structures are presented.

KEYWORDS: Bluff-body wake, turbulent boundary layer, coherent structure, counter rotating vortices, phase averaged flow.

1 INTRODUCTION

The prediction and control of wake transport processes requires an understanding of the turbulent coherent vortex structures due to the fundamental role they play in mixing and dispersion processes. The coherent structures in finite wall-mounted bluff body wakes give rise upon averaging to trailing streamwise vortex pairs [1-4]. In the vicinity of the obstacle tip, ‘free-end’ vortices induce downwash of flow toward the ground, while near the wall junction, ‘junction’ vortices induce upwash from below. As reported in [2-4], the junction vortex pair is not always present. The presence or absence of junction vortices can be of importance concerning safety for flow over stacks since the free-end vortex pair transports pollutants toward the ground when uninhibited by counter-rotating junction vortices. Similarly, the free-end downwash may be a concern in debris transport in strong winds over buildings which may endanger pedestrian traffic. Likewise, in combustor design using bluff-body flame stabilizer or fuel injection devices, the wall surface should be sheltered from hot gases in the core of the flow and a design ensuring junction vortices can meet this requirement.

While large differences in the mean and turbulent fields of the two wake types are observed (as discussed in [4] and presented in more details in the following), there is a lack of consensus on the parameters influencing the generation of these vortices. Sumner et al. [2] and Wang & Zhou [3], suggest that a sufficiently high aspect ratio h/d (where h is the height and d the width of the cylinder), will result in the presence of junction vortices. They, respectively, showed for circular- and square-cross-section cylinders that $h/d=3$ or less show dipole distributions of streamwise vorticity (only a free-end vortex pair) while $h/d=5$ or above show a quadrupole dis-

tribution of streamwise vorticity (free-end and junction vortex pairs). On the other hand, Wang et. al. [4] suggest that the boundary layer thickness (δ) plays an important role on presence of the upwash at the junction of the symmetry plane. They show for a cylinder with aspect ratio $h/d=5$ the upwash is present for a sufficiently thick boundary layer but it vanishes for a thin boundary layer. They suggest the effect of the boundary layer is less important for taller cylinders.

The present study aims to elucidate key role of the boundary layer by examining the flow around a rather tall building (with an aspect ratio clearly larger than the limit suggested in [2,3]) immersed in two very thin boundary layers with respect to the height. Using synchronized particle image velocimetry (PIV) and surface pressure measurements, the three-dimensional time averaged and phase averaged coherent structures in the wake of the cylinder are reconstructed and analyzed along with their respective velocity, vorticity, and Reynolds stress fields.

2 EXPERIMENTAL SETUP

The measurements were conducted in a suction type open-test-section wind tunnel shown in figure 1. A square cylinder with aspect ratio $h/d=8$ ($h=101.6mm$, $d=12.7mm$) was mounted on a sharp-leading-edge flat plate in the working section as shown in figure 2. The wake measurements were conducted for two turbulent boundary layers: the natural boundary layer developed over the flat plate and a tripped boundary layer with a $6.35mm$ rod positioned $1cm$ from the leading edge. The boundary layer thickness measured at the location of the obstacle ($x=200mm$ from the leading edge of the flat plate) with the cylinder removed was $\delta/h=0.09$ and 0.32 respectively. Boundary layer profiles and root-mean-square velocity fluctuations measured with hot-wire anemometers (TSI model 1210-20) are shown in figure 3. The free stream velocity was $U_\infty=15m/s$, corresponding to a Reynolds number $Re=U_\infty d/\nu=12,000$, with turbulent intensity of 0.8% . The measured Strouhal number was $St=fd/U_\infty=0.10 \pm 0.003$ with f the vortex shedding frequency. The Strouhal number was invariant with the change in boundary layer thickness.

A grid of several horizontal (x - y) and vertical (x - z) planes were measured using a LaVision FlowMaster high-frame-rate particle image velocimetry (PIV) system. These planar measurements are used to reconstruct the phase averaged three-dimensional flow. A pulse separation of $50\mu s$ was used and frame rates of 500 to 1000 Hz captured 4 to 8 data points per shedding cycle. The estimated uncertainty on individual vector measurements is $\Delta u/U_\infty=\pm 0.025$. Conditional sampling (phase averaging) of the PIV measurements was performed using the fluctuating surface pressure difference on opposing sides of the obstacle at $z=h/2$ as the instantaneous phase of the shedding cycle. The sampling rate for the pressure is 10.24 kHz and is synchronized with the PIV measurements using a TTL trigger. The shedding period is discretized into twenty equal phase steps, φ_n , ($\Delta\varphi=\pi/10$) between $\varphi=0$ and $\varphi=2\pi$. This number of bins was chosen as a compromise between statistical convergence and precision. A double decomposition ensemble average is undertaken for each phase step [5].

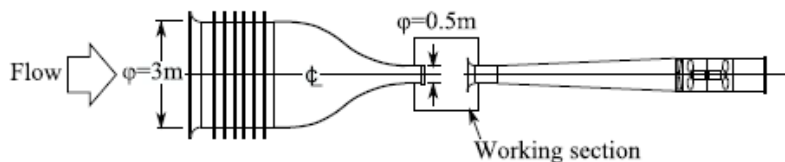


Figure 1. Schematic of the wind tunnel.

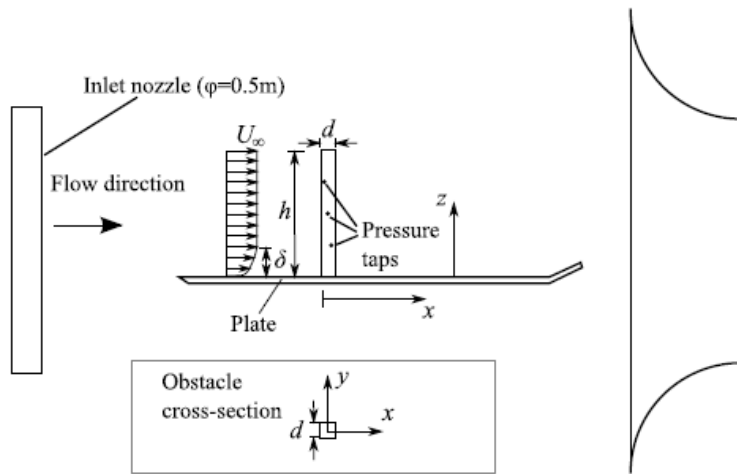


Figure 2. Schematic of the experimental setup inside working section (not to scale).

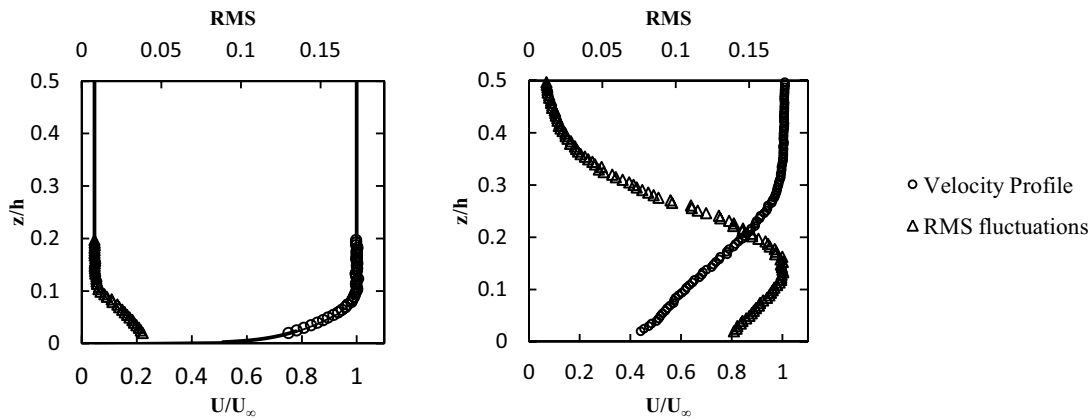


Figure 3. Natural and tripped boundary layer profiles and root-mean-square (RMS) velocity fluctuations at the location of the obstacle with the obstacle removed.

3 RESULTS

The boundary layer interactions with the vortex formation process results in topological differences both in the mean and dynamic fields. Figures 4 presents the mean sectional streamlines in the symmetry plane. For both the cases there is a downwash close to the free-end and an upwash in the base region at the junction. The separated streamlines from the free-end and the junction form a lee saddle point in the symmetry plane. The bifurcation lines extending from this saddle point separate the downwash region from the free-end and the upwash region near the mounting plate. For the thicker boundary layer (tripped case) the upwash at the junction is stronger thus the saddle point is located at a higher position. For the thinner boundary layer (untripped case), the upwash downstream of the saddle point is very weak. Similar observations were made in [4].

The mean streamlines at $z/h=0.25, 0.50$ and 0.75 are shown in figure 5. In general the recirculation regions are shorter in the tripped case. The largest difference is observed at the lower plane where for the untripped case the streamlines are diverging from the symmetry plane, in contrast to the tripped case where the streamlines converge onto the symmetry plane. The recirculation length is reduced largely for the tripped case while it stays almost the same as the middle plane in the untripped case.

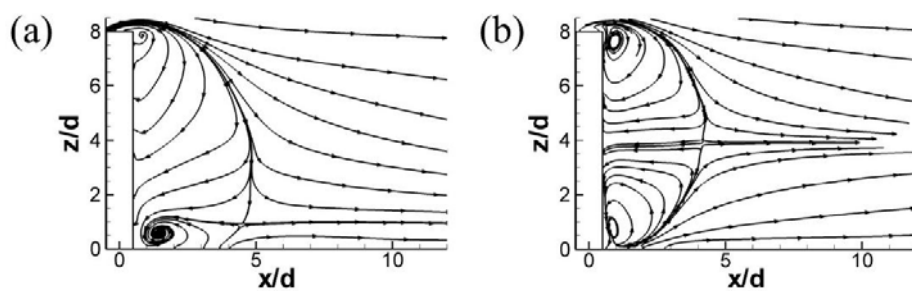


Figure 4. Mean flow streamlines in the symmetry plane for (a) untripped and (b) tripped cases. While the flow is similar close to the free-end, large differences are observed at lower heights.

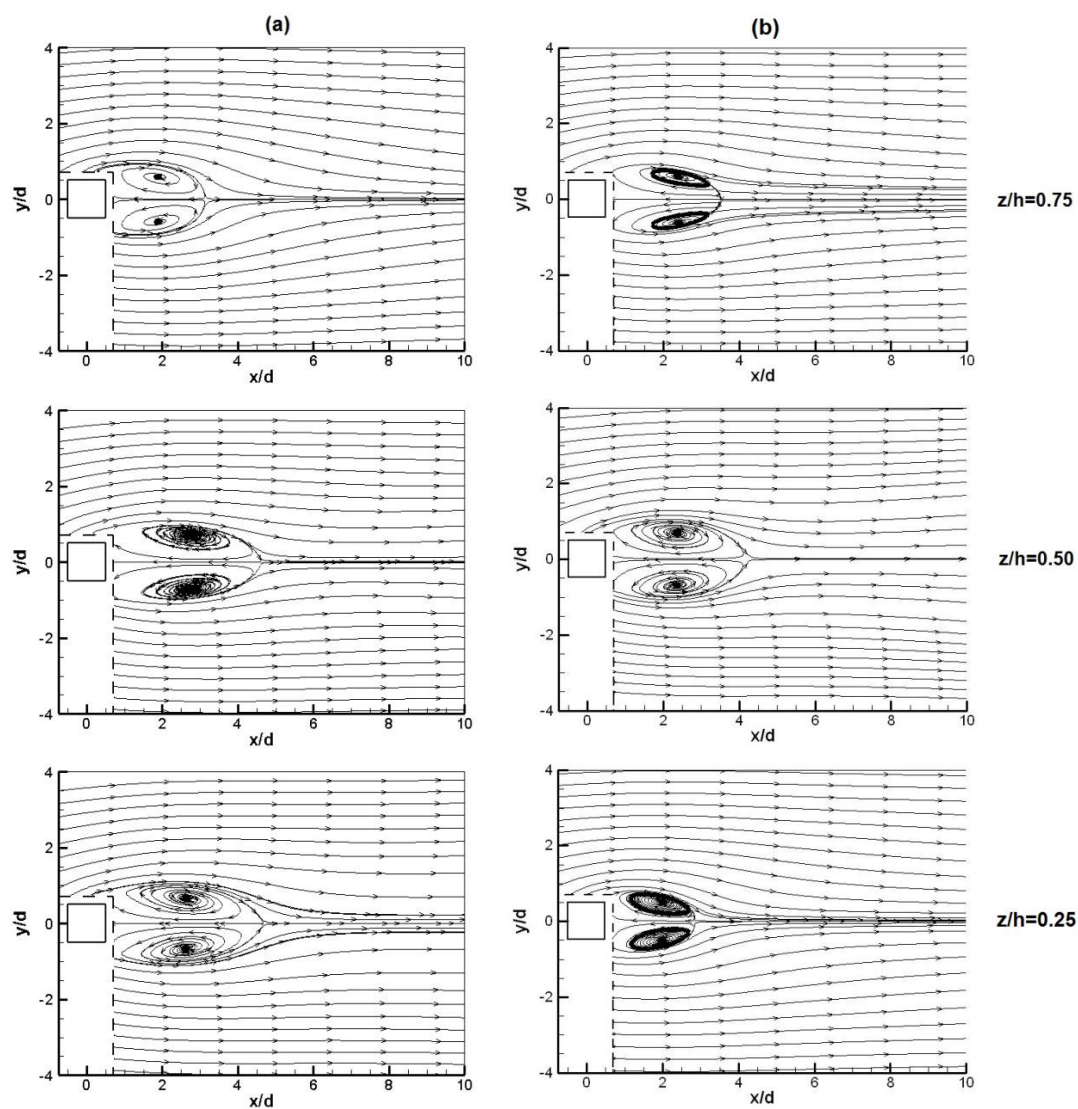


Figure 5. Mean flow streamlines in the symmetry plane for (a) untripped and (b) tripped cases. The largest differences are observed between the lower planes.

The mean vortex structures identified from λ_2 -criterion [6] are shown in figures 6. For the untripped case a counter rotating vortex pair is present close to the free-end (dipole type). For the tripped case, on the other hand, another counter rotating vortex pair is also observed at the junction (quadrupole type). The free-end vortices look very similar both in strength and shape. In the tripped case, however, they are pushed up by the strong upwash induced by the junction vortices.

The rotation direction of these vortex pairs is such that the free-end pair induces a downwash and the junction pair induces an upwash in the wake. Thus a stronger upwash at the junction in the symmetry plane is due to the formation of the stronger junction vortices in the thicker boundary layer case.

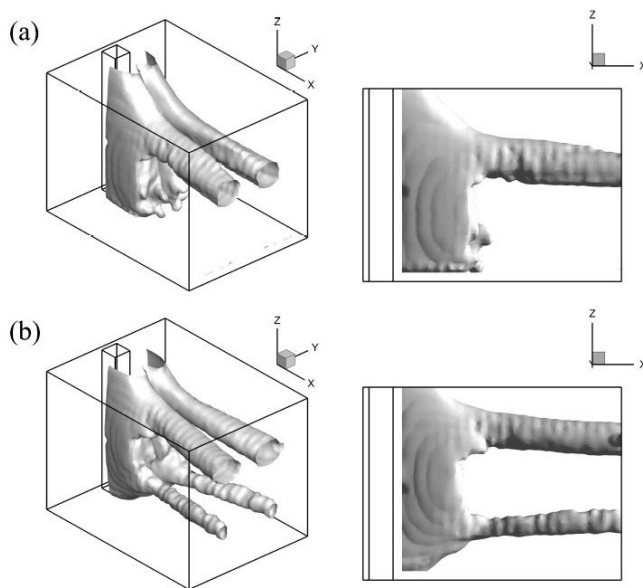


Figure 6. Mean vortex structure identified from λ_2 -criterion for (a) untripped and (b) tripped cases which are respectively referred to as dipole and quadrupole wakes.

The differences indicated in the mean fields are due to different shed structures formed in each types of wake. To this end, a phase average decomposition is conducted to elucidate the typical wake and shed vortices structure. To justify the use of this decomposition the velocity fluctuations were measured at several spanwise and streamwise locations with a hot-wire anemometer. The power spectra along the span at $x/d=4$ and $y/d=2$, obtained from three realizations each 20 second long, is shown in figure 7. For all positions the power spectra exhibits a sharp and prominent peak at $St=0.102 \pm 0.003$ which is associated with the periodic vortex shedding. The peak is broadened at $z/h=0.25$ and 0.75 in the tripped case and $z/h=0.75$ in the untripped case; which is an evidence for a disruption of the regular von Karman structures that are shed parallel to the cylinder axis. It should be noted that the Strouhal numbers for both cases are very close. This is consistent with [7] where they examine the Strouhal number changes as a function of boundary layer thickness and show that at small boundary layer thickness to height ratios the Strouhal number remains constant.

Even though the Strouhal numbers for both the cases are the same, the power distributions are clearly different. The sharper peaks in the untripped case suggest that the shed structures have a clearer periodic behavior, i.e., the behavior is more similar to the periodic von Karman structures. Another difference is in the energy distribution. In the untripped case a significant portion of the energy is distributed among the low frequency fluctuations. The higher frequency fluctua-

tions, however, are less strong compared to the tripped case. This can also be seen in figure 8 where the symmetric and anti-symmetric parts of the pressure fluctuations are shown. The symmetric part is the sum of the pressure signals measured at the opposite faces of the obstacle and the anti-symmetric part is the difference. For a truly periodic shedding the pressures at either side are two periodic signals with 180° phase shift. In a quasi-periodic shedding the sum represents the low frequency fluctuating part of the signal and the difference represents the high frequency fluctuations. Figure 8 shows that, the energy of the low fluctuations is slightly larger in the untripped case. The fluctuations in the anti-symmetric part, however, are stronger in the tripped case. It should be noted that with phase averaging only the periodic part of the high frequency fluctuations are categorized as coherent and the rest are assumed to be incoherent. As will be shown later, the coherent fluctuations obtained from phase averaging have the same level of energy and the difference is observed in the incoherent parts. These differences in the power distribution suggest that the shed structures behave differently.

Figure 9 shows the phase averaged vortical structures identified from λ_2 -criterion. For both the cases the structures are shed alternatively from either side of the obstacle. In the dipole case the structure is connected to the ground almost vertically while is bent streamwise close to the free-end forming a half loop shape. In the tripped case, the shed structures are turned around both at the free-end and the junction forming a full loop shape. As shown in the figure the vertical part is called principal core and the streamwise part is called connector strand. The principal cores shed similar to the von Karman structures and thus they behave similarly. The connector strands, on the other hand, have a different form and thus their imprint is distinct. The broader peaks and higher level of non-periodic fluctuations in the tripped case, for example, are due to the presence of this non-von Karman type structures. By time averaging, connector strands give rise to streamwise vortex pairs. Thus time averaging of the half loop and full loop structures results in respectively the dipole and quadrupole wakes shown in figure 6.

To illustrate the significance of the shed structures in the turbulent field, contours of time-averaged squared lateral velocity fluctuations, $\overline{v'^2}$, as well as the recirculation region boundaries are plotted in figure 10 in three horizontal planes. The effect of the connector strands in the planes close to the strands, i.e., at $z/h=0.75$ in the untripped case and $z/h=0.25$ and 0.75 in the tripped case, can be seen as reducing the recirculation length and introducing three-dimensionality into the wake distribution. The recirculation length for a two-dimensional shedding is approximately the same as the vortex formation length, i.e., the distance downstream of the bluff body where the fluctuations reach the maximum value [8]. In these planes, however, the maximum fluctuation occurs farther downstream of the saddle point at the end of the recirculation region.

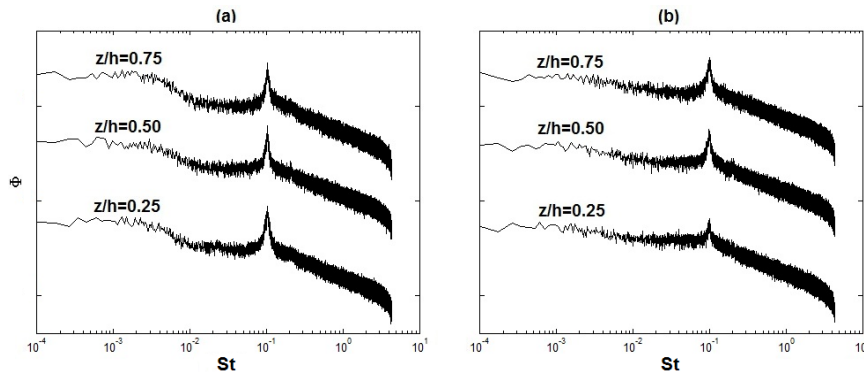


Figure 7. Power spectral density functions for (a) untripped and (b) tripped cases at $x/d=4$ and $y/d=2$. Spectra at $z/h=0.50$ and 0.75 are offset for clarity.

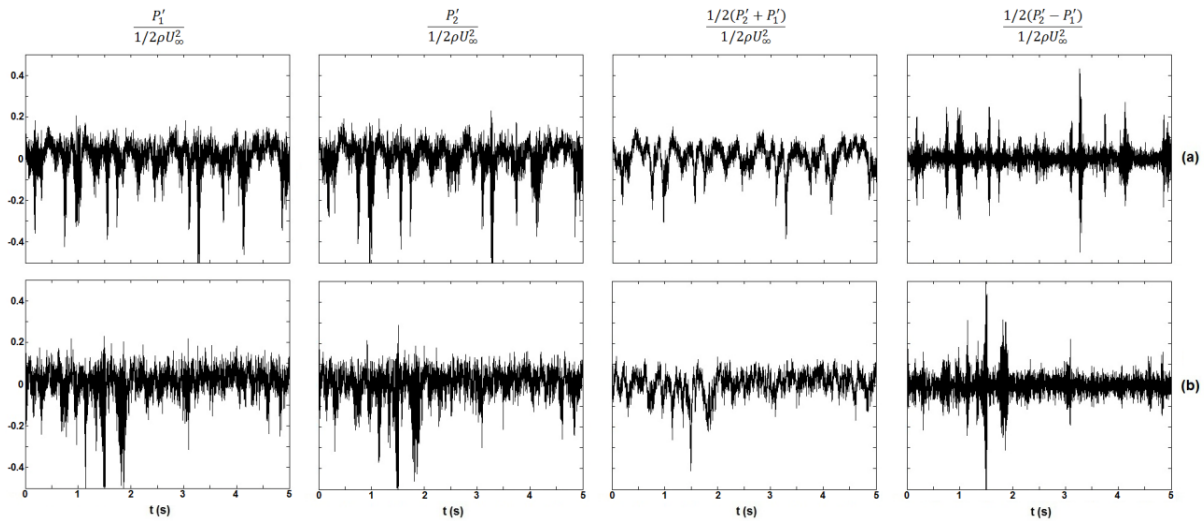


Figure 8. The pressure signals and the symmetric and anti-symmetric parts at $z/h=0.25$ for (a) untripped (b) tripped cases.

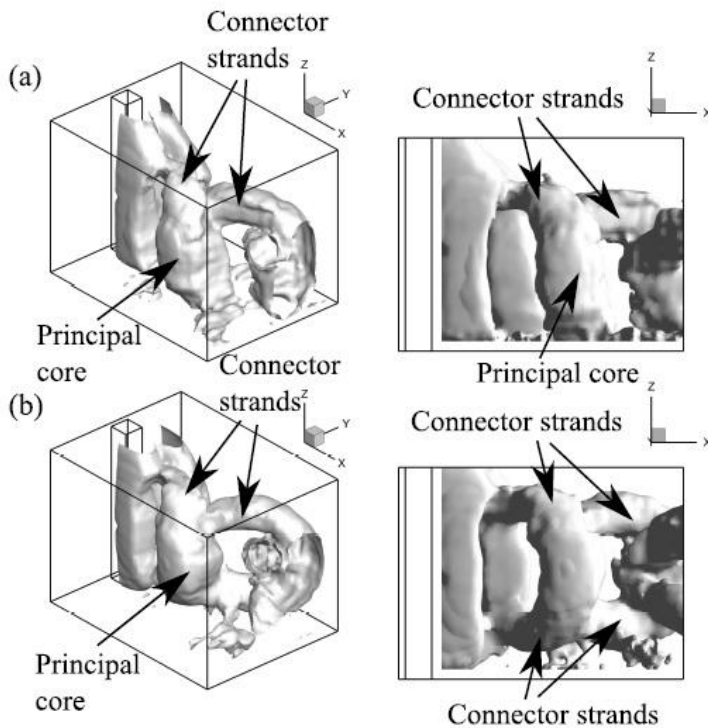


Figure 9. Half loop and full loop vortical structures, identified from λ_2 -criterion, shed alternately from either side of the cylinder in (a) dipole (b) quadrupole wakes.

Another effect of the strands is decreasing the shear layer width and as discussed before enhancing the level of fluctuating energy. The maximum level of lateral fluctuations in the lower and upper planes in the tripped case is enhanced by more than 25% compared to the middle plane. Note that for the untripped case the connector strands are located at a lower position and thus this effect is not seen at $z/h=0.75$.

Figure 11 shows contours of w'^2 at the symmetry plane. In the untripped case there is one maximum at the top while for the tripped case there are two maxima (with the same order of

magnitude) at the top and the bottom, close to the connector strands. Thus it can be concluded that the connector strands enhance the level of vertical fluctuations greatly. It should also be noted that for the present case, the full loop structures are almost symmetric and therefore the top and bottom strands act similarly.

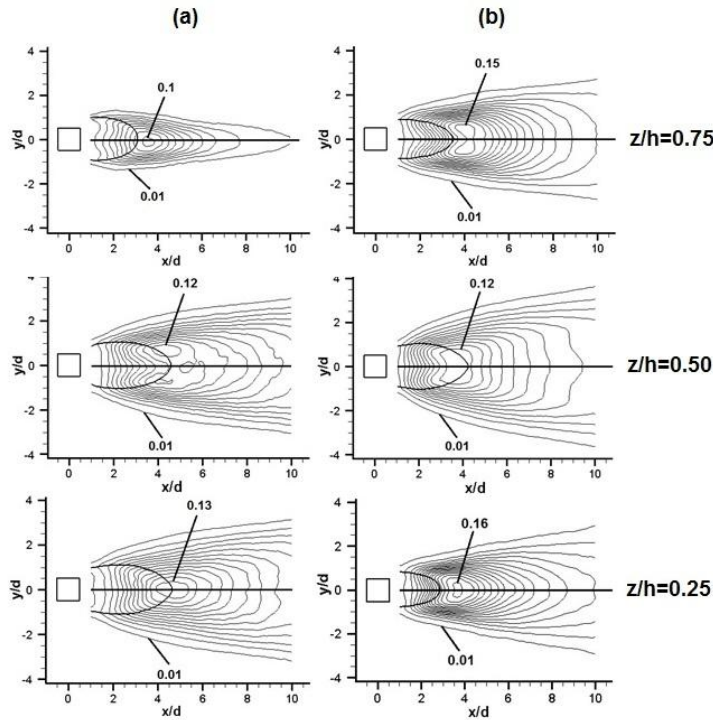


Figure 10. Contours of lateral fluctuations at $z/h=0.25$, 0.50 and 0.75 for (a) utripped and (b) tripped cases. The maximum fluctuation is located farther downstream of the end point of the recirculation region in the planes close to the connector strands.

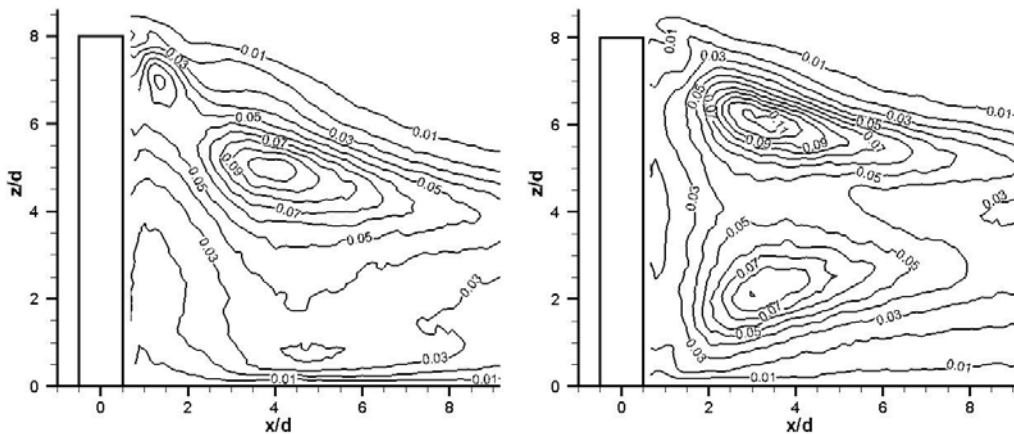


Figure 11. Contours of constant w'^2 for utripped (left) and tripped (right) boundary layers. The connector strands enhance the level of fluctuating energy.

From figures 10 and 11, it is concluded that in the planes close to the connector strands the total fluctuation level is increased. In figure 12 contours of total lateral fluctuations (repeated for the sake of comparison) as well as the coherent and incoherent parts are plotted for planes at

$z/h=0.25$ for both the wakes. This figure reveals that the increase in the lateral fluctuating level in the tripped case is due to the enhancement in the incoherent fluctuations, i.e., the parts that are not periodic as the regular von Karman structures. It could be argued that this increase could be due to the boundary layer effects since the tripped boundary layer is extended to this plane ($\delta/h=0.32$). Figure 13, however, shows that the same trend is observed in the plane close to the top strands, i.e. $z/h=0.75$, where compared to the middle plane the maximum level of incoherent fluctuations is larger. Thus the passage of the connector strands can be seen as an increase in the non-periodic fluctuating energy.

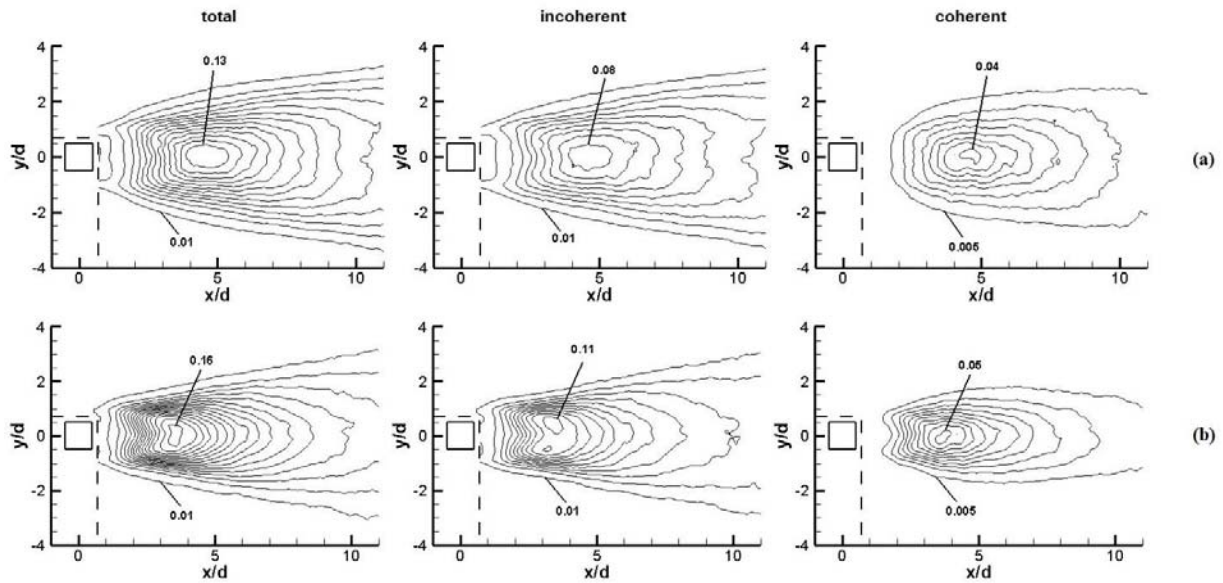


Figure 12. Decomposition of v'^2 into coherent and incoherent components for (a) untripped (b) tripped cases at $z/h=0.25$. The increase in the total fluctuating energy in the tripped case is mostly due to the increase in the non-periodic fluctuations which are categorized as incoherent in phase averaging.

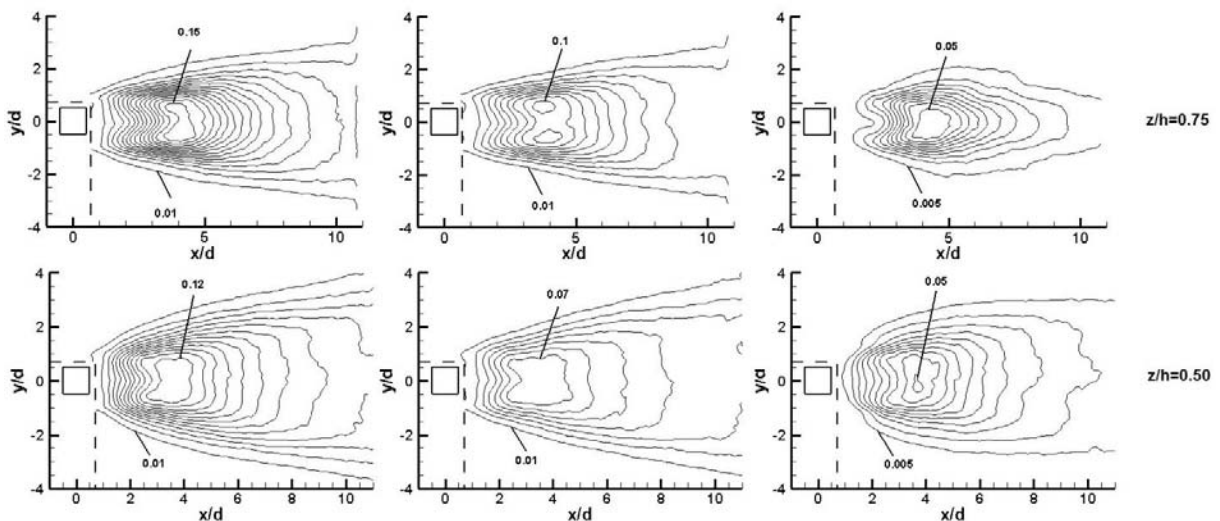


Figure 13. Decomposition of v'^2 into coherent and incoherent components for the tripped case.

4 CONCLUSION

The flow behind a tall square cylinder ($h/d=8$) mounted on a flat plate immersed in two thin boundary layers ($\delta/h=0.09$ and 0.32) is visualized using a 2-D PIV system. The three-dimensional phase averaged coherent structures are reconstructed from the velocity field at several horizontal and vertical planes measured simultaneously with the surface pressure as the reference signal. While the previous studies suggest that for cylinders immersed in thin boundary layers with aspect ratio taller than 3 the quadrupole wake is expected, the present work shows that depending on the boundary layer thickness both the wake types can form. This demonstrates the key role of the boundary layer even for boundary layers as thin as the ones considered here.

The shed structures form a half loop shape in the dipole wake and full loop shape in the quadrupole wake. The time averaging of these shed structures give rise to the different mean vortex distribution. The structures shed anti-symmetrically from either side of the obstacle and no evidence of symmetric shedding is observed.

The practical significance is in the large deviation of the wake distribution between the two cases. The rotation of the strands in the streamwise direction alters the mean and turbulent field greatly. The recirculation length is shortened and no longer coincides with the formation length as it does in two-dimensional shedding. The level of lateral fluctuating energy is increased by more than 25%; this increase is in the incoherent fluctuations. The distribution of the vertical velocity fluctuation is also altered highly. In the dipole wake only one maximum is observed close to the free-end while in the quadrupole wake another maximum with the same order of magnitude is observed close to the junction. Due to the large vertical velocities induced by the strands the wake width is reduced in the planes close to the strands.

All these effects are observed in the planes in proximity to the connector strands, i.e., $z/h=0.75$ in the dipole wake and $z/h=0.25$ and 0.50 in the quadrupole wake. Thus the largest difference between the two wakes is present at the lower plane, which is influenced by the strands in the quadrupole wake but remains undisturbed in the dipole wake. This is particularly important in predicting the wake load of tall buildings on pedestrians.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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