Influence of surface topology on boundary layer and near-wake behavior of rectangular cylinders

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A study is carried out to investigate the effect of surface topology on the boundary layer and the near-wake flow around a rectangular cylinder with side-ratio of 2.5 and fully-round corners (half-circular leading and trailing edges) at a Reynolds number based on thickness of \( Re_d = 2,500 \). The topology is defined using Fourier modes with an amplitude of 5\% of the thickness, along the perimeter only (2D geometry) as well as along the perimeter and the span (3D geometry) of the cylinder. The study is motivated by understanding the flow around parachute suspension lines, which exhibit geometrical features and parameters that, while not an exact replica of, are reasonably represented by the canonical geometry investigated. Single-component molecular tagging velocimetry is employed to measure the streamwise velocity profiles at different streamwise locations above the surface and in the wake of the cylinder. Profiles of the mean and the root-mean-square velocity are employed to analyze the development of the boundary layer and the separated flow on the cylinder at three positive angles of attack: \( \alpha = 0^\circ, 2^\circ \) and \( 5^\circ \). Results show that the most significant effect of the surface topology is found when a peak in the topology resides at the leading edge (LE). In this case, separation occurs earlier, and the separated shear layer is thicker, displaced farther away from the cylinder and exhibits stronger unsteadiness than the smooth cylinder and the cylinder with topology with a valley at the LE. These observations hold for both the 2D and the 3D topology, with some differences between both seen at \( \alpha = 0^\circ \) and \( 2^\circ \). At \( \alpha = 5^\circ \), these differences are not very significant, and the 2D profiles reasonably approximate those of the sectional 3D flow. Finally, examination of the streamwise evolution of the wake mean centerline velocity \( \bar{U}_c \) at \( \alpha = 0^\circ \) demonstrates that the reverse-flow and the closure length in the near-wake are only affected slightly by the presence of surface topology for both 2D and 3D geometries. Farther downstream, the smooth-cylinder and the 3D topology exhibit similar \( \bar{U}_c \) streamwise evolution, leading to “far-wake” behavior that is different from the 2D geometry.

I. Nomenclature

\[
\begin{align*}
C_d &= \text{drag coefficient} \\
C_L &= \text{lift coefficient} \\
C_y &= \text{transverse-force coefficient} \\
c &= \text{cylinder chord} \\
d &= \text{cylinder thickness} \\
F_D &= \text{drag force} \\
F_L &= \text{lift force} \\
F_y &= \text{transverse force} \\
l &= \text{cylinder span} \\
n &= \text{number of surface topology cycles around the cylinder perimeter} \\
p &= \text{cylinder perimeter} \\
Re_d &= \text{thickness-based Reynolds number; } U_\infty d / \nu \\
r &= \text{cylinder corner radius} \\
s &= \text{coordinate along the cylinder perimeter} \\
U_c &= \text{mean velocity on the wake centerline} \\
U_r &= \text{instantaneous freestream velocity relative to the cylinder} \\
U_\infty &= \text{freestream velocity} \\
u_{rms} &= \text{fluctuating-streamwise-velocity root mean square} \\
x &= \text{streamwise coordinate relative to cylinder center}
\end{align*}
\]

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\[ y = \text{cross-stream coordinate relative to cylinder center} \]
\[ z = \text{spanwise coordinate} \]
\[ \alpha = \text{angle of attack (AoA)} \]
\[ \Delta t = \text{time difference between 1c-MTV image pair} \]
\[ \epsilon = \text{surface topology} \]
\[ \epsilon_o = \text{surface topology amplitude} \]
\[ \lambda_s = \text{surface topology wavelength along the cylinder perimeter} \]
\[ \lambda_x = \text{surface topology wavelength along the cylinder span} \]
\[ \nu = \text{fluid kinematic viscosity} \]
\[ \rho = \text{fluid density} \]

II. Introduction

Bluff bodies may be susceptible to a flow induced instability known as galloping, which results in large-amplitude self-sustained vibration. Transverse galloping arises from the fact that the aerodynamic forces on the body change with its orientation to the oncoming flow. Considering a cylinder with a non-circular cross section mounted elastically in the transverse direction (y-direction in Fig. 1), the oscillatory motion velocity (\( \dot{y} \)) in the transverse direction will change the effective angle of attack \( \alpha \), or AoA, with time, thereby changing the lift (\( F_L \)) and the drag (\( F_D \)) forces. The corresponding change in the transverse-force (\( F_y \)) coefficient with \( \alpha \) can be calculated from the lift and drag coefficients from Equation 1.

![Schematic of cross section of the cylinder with zero amplitude topology and forces acting on it upon oscillating in the transverse (y) direction](image)

Fig 1. Schematic of cross section of the cylinder with zero amplitude topology and forces acting on it upon oscillating in the transverse (y) direction

\[ C_y = \frac{F_y}{0.5 \rho U_{\infty}^2 d \Delta t} = - \frac{1}{\cos^2 \alpha} (C_L \cos \alpha + C_D \sin \alpha), \]

where the lift and the drag coefficients (\( C_L \) and \( C_D \), respectively) are calculated as below:

\[ C_L = \frac{F_L}{0.5 \rho U_{\infty}^2 d \Delta t}, \]

\[ C_D = \frac{F_D}{0.5 \rho U_{\infty}^2 d \Delta t}. \]

In the above equations, \( U_{\infty} \) and \( U_r \) are the steady freestream and the instantaneous oncoming (relative to the moving cylinder) velocities, respectively, \( \rho \) is the fluid density, \( d \) is the baseline cylinder width, and \( l \) is the cylinder span. Galloping can occur when \( F_y \) increases with increasing the angle of attack; hence, reinforcing the oscillation and making the structure unstable [1]. In air flows, the natural frequency of the structure is typically sufficiently smaller than that of vortex shedding, in which case the flow behavior is quasi-steady. Accordingly, the relevant criterion for instability to galloping is based on the variation of \( F_y \) with \( \alpha \) for a static cylinder [1].

Many structures such as power lines, bridges, and others with non-circular cross section can experience galloping under certain conditions [1]. Another example is the suspension lines of precision airdrop systems (PADS), which have been recently shown to be susceptible to galloping [2-3]; with possible consequent negative effect on the performance and the controllability of PADS. The cross-section of these suspension lines is typically non-circular and resembles a rectangle with rounded corners, as given in Fig. 1. Additionally, due to braiding, the surface of the lines is not smooth, but is rather characterized by topological surface height variations [2-3]. Thus, it is important to understand the effect of the surface topology of these suspension lines on their aerelastic behavior; specifically, their \( F_y - \alpha \) characteristics.
In a recent study [4], we observed that the presence of the surface topology can change the galloping stability of cylinders of the same geometry as shown in Fig. 1, for Reynolds numbers $Re_d = U_\infty d/\nu$ from 1,100 to 10,000. These conclusions were made based on measurement of the transverse force coefficient ($C_y$) variation with AoA for the cylinders. To understand the basic characteristics of the flow field associated with the changes in the $C_y - \alpha$ behavior with surface topology, the current work focuses on understanding the boundary layer development on the cylinder surface at different angles of attack, and how this development is affected by the surface topology. This is accomplished using one-component Molecular tagging velocimetry (1c-MTV) to measure the streamwise velocity profiles within the boundary layer at different points along the surface of the model. These measurements, which also extend into the wake of the model, are done for cylinders with prescribed surface topology and compared to their counterpart on a smooth-surface model. The Reynolds number of the experiments is $Re_d = 2,500$, which falls in the range 1,000-10,000, relevant to the operation of PADS.

### III. Experimental Setup and Methods

The experiments are conducted in a closed-return, free-surface water tunnel (Engineering Laboratory Design, ELD) at the Turbulent Mixing and Unsteady Aerodynamics Laboratory (TMUAL) at Michigan State University. The tunnel has a test section with dimensions of 152 mm $\times$ 152 mm $\times$ 457 mm, and the test model is mounted in the test section from the free-surface side using a Plexiglas skimmer plate, as depicted in Figure 2a, to provide a well-defined end boundary condition. This skimmer plate extends approximately 76 mm (5.1 $d$) upstream and downstream of the model’s center, and spans the full width of the test section. The cylinder models are 3D printed with an 11.4 mm–diameter through hole along the model’s centerline, in which a tight-tolerance 304 stainless steel shaft is inserted in order to strengthen the models and prevent them from warping. This metallic shaft passes through the skimmer plate and is clamped using a bracket to a Parker manual rotary stage (model number 2535) which has an accuracy of $\pm 0.1^\circ$. The cylinder’s root and tip maintain clearance gaps of 0.5 mm (3.3% $d$) with the skimmer plate and the test-section bottom. The test-section geometrical blockage due to the cylinder width is 9.8% (at $\alpha = 0^\circ$).

![Diagram](image-url)

**Fig 2.** (a) 3D model of the experimental setup in the test section. (b) Schematic of the top view of the optical system for 1c-MTV measurements, and the tunnel test section.
The experiments are carried out at a Reynolds number of $Re_D = 2,500$, based on cylinder thickness and freestream velocity of $U_\infty = 14.8 \text{ cm/s}$, at water temperature of $25^\circ \text{C}$. The freestream turbulence intensity of the tunnel, based on the streamwise-velocity fluctuation, is around $1.2\%$. The centerline of the cylinder model is located $13.3d$ downstream of the entrance of the test section, and the freestream velocity is measured at the same location as, but in the absence of, the model. The presence of the model is verified to have a negligible effect on the freestream velocity.

One-component molecular tagging velocimetry (1c-MTV) is utilized to measure the flow velocity. MTV is a whole-field non-intrusive measurement technique that relies on using a flowing medium premixed with molecules that can be turned into long-lifetime tracers upon excitation by photons of a particular wavelength [5-6]. Typically, a pulsed laser is used to “tag” the regions of interest, and those tagged regions are interrogated at two successive times within the lifetime of the tracer. The measured displacement vector, divided by the time delay between interrogations, provides the estimate of the velocity vector. In addition, visualization can be done with the same method by increasing the time delay between exciting the tracers and capturing the image to allow for appreciable deformation of the tagging lines by the flow features in order to reveal their character. Figure 3 displays an example visualization of the boundary layer profiles on the smooth-cylinder surface. The long time delays of the visualization are not suitable for velocimetry due to the associated large displacement of the fluid molecules, among other complications.

![Figure 3: Boundary layer visualization on the smooth cylinder using MTV with inter-image time delay $\Delta t = 9 \text{ ms}$. Dashed lines represent the location of the undelayed tagging lines and the surface of the cylinder is marked in red](image)

The present implementation of MTV employs a phosphorescent supramolecule tracer [5] excited by a Lambda Physik LPX 210i XeCl 308 nm UV excimer laser. An optical system consisting of a series of coated mirrors and lenses is used to form a thin laser sheet, and to steer and direct the sheet through a beam blocker, which transforms the sheet into several individual tagging lines for 1c-MTV measurements, as depicted in Fig. 2b. The optical system is mounted on a three degree-of-freedom traversable optics bench, installed on the tunnel. The laser lines enter the test section on the side where quartz window inserts are installed. Other test section walls are made out of Plexiglas, which enables imaging of the molecular emission while blocking the UV laser light from exiting the test section.

One-component MTV measures the Lagrangian displacement of the fluid particles in the direction normal to a tagging line at every pixel along the line, providing one component of the flow velocity at very high spatial resolution. The technique for calculating the line displacement using spatial correlation is described in [7]. For the present work, the tagged lines are oriented to measure the streamwise velocity component with a spacing of 82 $\mu \text{m}$ ($0.006d$) along each of the lines. This high spatial resolution makes 1c-MTV particularly suited for boundary-layer-resolved measurements. A total of eight MTV lines are used in the measurements, stretching between $x/d = -1.19$, near the leading edge (LE), to $x/d = 0.99$, near the trailing edge (TE). With the lines equally spaced in the streamwise direction, the streamwise spacing of the measured velocity profiles is $0.32d$. A second set of measurements is obtained after displacing the lines in $x$ by half the line spacing; thus, halving the measurement streamwise spacing of the combined data set.

The time delay $\Delta t$ between the two MTV images (aka “un-delayed” and “delayed” images) is set to 5 ms for boundary layer measurements and 3.5 ms for wake measurements. The exposure time of the images is 500 $\mu \text{s}$ for boundary layer measurements and 350 $\mu \text{s}$ for wake measurements, during which a particle translates a negligible distance of 74 $\mu \text{m}$ and 52 $\mu \text{m}$, respectively, at the freestream velocity. For each case investigated, 292.6 s-long time series are acquired at a sampling rate of 7 images/s. The duration of the time series corresponds to almost 3000 convective times ($d/U_\infty$). Uncertainty analysis for the mean and the root mean square (rms) velocity measurements are reported in Table 1. In the table, the largest uncertainty found at all measurement locations is listed along with the mean uncertainty over the entire flow domain.
Table 1 - Uncertainty of mean and rms velocity measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean velocity convergence</td>
<td>$9 \times 10^{-5} U_\infty$</td>
<td>$3.7 \times 10^{-4} U_\infty$</td>
</tr>
<tr>
<td>Subpixel accuracy of the mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean velocity total uncertainty</td>
<td>$6.2 \times 10^{-4} U_\infty$</td>
<td>$6.3 \times 10^{-4} U_\infty$</td>
</tr>
<tr>
<td>RMS velocity convergence</td>
<td>$1.4 \times 10^{-3} U_\infty$</td>
<td>$1.25 \times 10^{-2} U_\infty$</td>
</tr>
</tbody>
</table>

The geometric parameters of the test models are selected such that they approximate typical Dacron parachute suspension lines. The basic cross-sectional dimensions of the baseline (smooth cylinder) model are $d = 15$ mm, $c = 37.5$ mm, and $r = 7.5$ mm, corresponding to a side ratio $c/d = 2.5$, and a fully-round LE and TE, $r/d = 0.5$ (see Fig. 1). The span of the models is $l = 139.6$ mm, which extends over the full height of the test section and results in an aspect ratio of 9.3. An idealized definition is used to prescribe the surface topology, instead of using a replica of the actual Dacron’s line geometry. This is motivated by two factors: first, the present study aims at providing general basic understanding of the effect of surface topology independent of specific applications; second, the idealized topology is defined precisely using two-dimensional Fourier-mode synthesis. Specifically, the topology $\varepsilon$ (see Fig. 4), which is the deviation of the cylinder surface from the baseline smooth cylinder cross-section, is given as follows:

$$
\varepsilon = \frac{\varepsilon_0}{2} \left[ \cos \left( 2\pi \left( \frac{s}{\lambda_s} + \frac{z}{\lambda_z} \right) \right) + \cos \left( 2\pi \left( \frac{s}{\lambda_s} - \frac{z}{\lambda_z} \right) \right) \right],
$$

(4)

where $s$ is the wall-tangential coordinate defined along the surface of the baseline (smooth) model, $z$ is the coordinate along the span of the cylinder, $\varepsilon_0$ is the topology amplitude, and $\lambda_s$ and $\lambda_z$ are the topology wavelengths in $s$ and $z$ directions, respectively (see Fig. 4). The wavelength along the $s$ direction is equal to $P/n$ with $P$ and $n$ being the baseline model’s perimeter, and the integer number of topology wavelengths around the perimeter, respectively.

![Fig. 4. Top and cross-sectional views of the cylinder with $\varepsilon_0/d = 5\%$, $n = 10$, and $\lambda_z/\lambda_s = 1.5$](image-url)
To systematically study the effect of the surface topology, several models are investigated, in addition to the main geometry shown in Fig. 4. A model with zero topology amplitude (i.e. smooth cylinder) is employed as a baseline case. A second set of models is made with surface topology, where the cross section is constant along the whole span ($\lambda_s = \infty$). This set, which is referred to as the 2D set, includes two different cross-section shapes: one with a peak in the topology at the LE, and the other with a valley. These “peak-leading” and “valley-leading” shapes are exactly the same as those found at cross-sections A-A and B-B of the 3D cylinder geometry in Fig. 4. The 2D models are used to study the effect of the topology on the flow in the absence of flow three-dimensionality induced by the spanwise waviness of the topology. Comparing results from the 2D models to those from the 3D model is expected to provide insight into the significance of the spanwise variation of the topology. For approximation of a Dacron cable geometry, $\lambda_x/\lambda_s = 1.5$ and $n=10$ are chosen for the cylinders used in the present study. The topology amplitude is $\varepsilon_0/d = 5\%$ for all cases.

IV. Results and Discussion

A. Boundary-Layer Characteristics: Mean Velocity

Figure 5 shows the mean-velocity profiles for the smooth cylinder (black lines), compared with those for the cylinders with 2D surface topology (red lines) with peak (solid lines) and valley (broken lines) at the leading edge. The results are shown for three different angles of attack: $\alpha = 0^\circ$, $2^\circ$ and $5^\circ$ but only for every other streamwise location to avoid clutter of the profiles. In addition, although the actual streamwise locations of the measurements for the different cylinder models are not exactly collocated, the difference, which is mostly less than half a tick mark of the $x/d$ axis, is ignored in presenting the data to facilitate comparison between the profiles. Similarly, only the baseline, smooth, cylinder geometry is superposed on the figure, to avoid superposing multiple model shapes on the same figure.

Considering the smallest AoA and the smooth cylinder, the boundary layer at the most upstream measurement location (just downstream of the round corner) appears to be attached. While not directly observable from Fig. 5, at the next downstream position, the boundary layer separates. This is determined from the presence of reversed flow near the wall, as will be discussed below in connection with Fig. 7. The specific boundary layer separation location cannot be determined precisely in the present work due to limited spatial resolution near the wall which is aggravated in the presence of topology (an issue that will be addressed in future work). In addition to the separation of the boundary layer, the velocity profile also develops an inflection point, where the cross-stream velocity gradient is highest along the cross-stream direction. Above the reversed-flow region, this profile reflects the presence of a separated shear layer.

Comparing the smooth-cylinder profiles to those of the cylinder with 2D topology, significant differences are seen when the topology possesses a peak at the leading edge. Specifically, in the latter case, the flow is already separated by the first measurement location and the separated shear layer is displaced farther away from the cylinder. The earlier development of the shear layer seems to lead to larger shear layer thickness, in comparison to the smooth cylinder. In contrast, the development of the boundary layer for the 2D topology with a valley at the LE, while exhibiting some differences, is not drastically altered from that on the smooth cylinder.

The above observations at $\alpha = 0^\circ$ are generally similar to those seen at the higher angles of attack. One effect of increasing the AoA, that is common to all cases, is the increasing lateral displacement of the separated shear layer away from the cylinder. In fact, the displacement becomes sufficiently large at $\alpha = 5^\circ$ that the reverse flow region extends all the way to the most downstream location (see Fig. 7), suggesting the presence of an open separation for all cases. Under these conditions, while the peak-leading 2D-topology velocity profiles remain significantly different from the smooth cylinder and the valley-leading-topology profiles along most of the surface, the profiles are not significantly different by the most downstream location.
Fig 5. Comparison between the boundary layer mean-velocity profiles on the cylinders with smooth surface (black lines) and 2D surface topology (red lines) at different angles of attack: $\alpha = 0^\circ$ (top), $2^\circ$ (middle), $5^\circ$ (bottom). Solid and broken lines depict results for surface topology with peak and valley at the LE, respectively. Only the nominal (smooth) cylinder geometry is shown to avoid clutter. Profiles on top of topology peaks terminate above the nominal geometry and those on top of valleys are truncated at the surface. Flow is from left to right. The velocity scale is indicated on plots with a horizontal black line.

To examine the effect of three-dimensionality of the topology, Fig. 6 provides a comparison similar to Fig. 5, but with the smooth-cylinder results replaced with those for the cylinder with 3D topology (blue lines). Unlike the smooth-cylinder results, the case of 3D topology involves two sets of data: one measured at a spanwise location where the topology has a peak at the LE (solid lines), and the other at a location displaced $\lambda_e/2$ from the first location; i.e. where a valley is present at the LE (broken lines). Focusing first on comparing the cases with a peak at the LE (solid red and blue lines for the 2D and 3D geometry respectively), the profiles at all angles of attack are initially similar for the two cases; i.e. early in the development of the boundary layer, Farther downstream, some deviation is seen between the two cases with the beginning of the deviation shifting farther downstream with increasing AoA. At the highest angle of attack, significant difference is only seen at the two most downstream locations. The deviation is such that the high-shear zone of the shear/boundary layer moves closer to the cylinder in the 3D compared to the 2D case.

For the valley-leading topology (broken lines in Fig. 6), no substantial deviation is seen between the 2D and the 3D case at $\alpha = 0^\circ$. On the other hand, at $\alpha = 2^\circ$ and $5^\circ$, the initial, most upstream, mean-velocity profiles are similar, but farther downstream, a deviation between the two profiles is observed. Unlike the peak-leading topology case at these two angles of attack, where the deviation increases with downstream distance, for the valley-leading case, the difference between the profiles is largest near the center of the cylinder. However, similar to the peak-leading topology, when a difference is observed between the 2D and the 3D cases, the high-shear zone in the profiles for the
valley-leading 3D topology is located closer to the cylinder. It is also noteworthy that, overall, the difference between the 2D and the 3D case is smallest at the largest AoA.

![Diagram](https://example.com/diagram.png)

**Fig 6.** Comparison between the boundary layer mean-velocity profiles on the cylinders with 2D (red lines) and 3D (blue lines) surface topology at different angles of attack: $\alpha = 0^\circ$ (top), $2^\circ$ (middle), $5^\circ$ (bottom). Solid and broken lines depict results for surface topology with peak and valley at the LE, respectively. Profiles on top of topology peaks terminate above the nominal geometry and those on top of valleys are truncated at the surface. Flow is from left to right. The velocity scale is indicated on plots with a horizontal black line.

Further information regarding the boundary layer behavior may be extracted by characterizing the separation zone. While it is not possible to pin-point the separation and the reattachment location with the present near-wall/streamwise measurement resolution, it remains feasible to characterize the overall shape of the separation zone. To do this, the reverse-flow region is identified by locating the zero-velocity crossing point away from the wall in each mean-velocity profile. For better clarity in comparing the results for different cases, the identified points at different streamwise locations are fit with a second-order polynomial to represent the separation zone top boundary. This fit form is the simplest allowing for curvature of the boundary while fitting the data well. The results for the cylinders with smooth surface and 2D topology are shown in Fig. 7 using the same line types and colors as employed in Fig. 5. Inspecting Fig. 7, it is clear that the 2D surface topology with a peak at the LE results in the thickest separation zone (largest cross-stream dimension) at all angles of attack. This is consistent with the larger cross-stream displacement of the shear layer from the cylinder for the same geometry, found earlier from analysis of the mean velocity profiles. On the other hand, when comparing the separation zone for the 2D valley-leading topology to that of the smooth cylinder, the former is thicker at $\alpha = 0^\circ$, but it becomes thinner at $\alpha = 5^\circ$ with the two becoming comparable in thickness at the intermediate AoA of $2^\circ$. In addition, for all three model geometries, the results indicate that at the largest AoA, the flow on the upper surface separates and does not reattach (i.e. fully separated flow), as discussed earlier.
Fig 7. Comparison between the separation-zone boundary on the cylinders with smooth surface (black lines) and 2D surface topology (red lines) at different angles of attack: $\alpha = 0^\circ$ (top), $2^\circ$ (middle), $5^\circ$ (bottom). Solid and broken lines depict results for surface topology with peak and valley at the LE, respectively. Only the nominal (smooth) cylinder geometry is shown to avoid clutter. Flow is from left to right.

The separation-zone boundary for the cylinder with 2D topology is compared to that for the 3D counterpart in Fig. 8. Focusing first on the topology with a peak at the LE, it is evident that the boundary is similar at the upstream end but it deviates farther downstream with the boundary for the 3D topology curving earlier towards the cylinder. This implies that the streamwise extent of the separation zone is shorter for the 3D case with a peak at the LE. Moreover, the similarity of the boundary at the upstream end might indicate that the separation location is the same; i.e. uninfluenced by the three-dimensionality of the topology. This, however, cannot be ascertained in the absence of sufficient resolution near the wall. In contrast to the peak-leading surface topology, rather surprisingly, the three-dimensionality of the valley-leading surface topology does not seem to lead to a substantial difference in the separation zone boundary from that of the 2D topology. Furthermore, the shape of the separation zone for both the 2D and the 3D topology alludes to an earlier (farther upstream) separation, and a thicker separation zone, for the topology with a peak at the LE. The aforementioned observations pertain to all three angles of attack.
Fig. 8. Comparison between the separation-zone boundary on the cylinders with 2D (red lines) and 3D (blue lines) surface topology at different angles of attack: $\alpha = 0^\circ$ (top), $2^\circ$ (middle), $5^\circ$ (bottom). Solid and broken lines depict results for surface topology with peak and valley at the LE, respectively. Profiles on top of topology peaks terminate above the nominal geometry and those on top of valleys are truncated at the surface. Flow is from left to right.

B. Boundary-Layer Characteristics: Fluctuating Velocity

The unsteadiness of the flow is examined by inspecting the root-mean-square ($rms$) profiles of the fluctuating velocity components ($u_{rms}/U_\infty$). These results are shown in Fig. 9 and Fig. 10 with the comparison between the different cases organized in the same manner as for the mean-velocity profiles. Referring to Fig. 9, it is clear that the topology with a peak at the LE produces the highest level of fluctuation over most of the cylinder surface at all angles of attack. Moreover, the location of the maximum $u_{rms}$ is displaced farther away from the cylinder, and the lateral spread of the fluctuation is largest in comparison to the smooth and the valley-leading geometry. The difference in this spread does become smaller with increasing angle of attack with all cases showing comparable spread at the highest AoA and the most downstream location of the measurements. All together, these observations suggest a separated shear layer behavior that is consistent with that implied from the mean-velocity profiles. Specifically, the presence of a peak at the LE causes the development of a shear layer that is thicker and displaced farther away from the model in comparison to the other cases. This shear layer also produces the highest velocity fluctuation.
Fig 9. Comparison between $u_{rms}/U_\infty$ profiles along the cylinders with smooth surface (black lines) and 2D surface topology (red lines) at different angles of attack: $\alpha = 0^\circ$ (top), $2^\circ$ (middle), $5^\circ$ (bottom). Solid and broken lines depict results for surface topology with peak and valley at the LE, respectively. Only the nominal (smooth) cylinder geometry is shown to avoid clutter. Profiles on top of topology peaks terminate above the nominal geometry and those on top of valleys are truncated at the surface. Flow is from left to right. The velocity scale is indicated on plots with a horizontal black line.

The effect of surface topology three-dimensionality on the velocity fluctuation is examined using Fig. 10. Comparing the $u_{rms}/U_\infty$ profiles for the 2D and the 3D geometry with a peak at the LE (solid lines), a trend consistent with that observed for the mean-velocity results emerges. In particular, early in the profile development on the upstream end, a relatively small deviation is observed between the two cases, but the deviation grows bigger with downstream distance. The start of the deviation shifts farther downstream with increasing AoA such that at the largest AoA of $5^\circ$, the profiles are quite similar along most of the cylinder surface. For the geometry with the valley at the LE, similar observations hold, except, like the mean-velocity profiles, the largest deviation between the 2D and the 3D geometry is found on top of the flat portion of the baseline geometry, near the middle of the cylinder. All together, the striking aspect of these results is that at $\alpha = 5^\circ$, the three-dimensionality of the geometry has a relatively small effect on the boundary layer/shear layer characteristics.
Fig 10. Comparison between $u_{rms}/U_\infty$ profiles along the cylinders with 2D (red lines) and 3D (blue lines) surface topology at different angles of attack: $\alpha = 0^\circ$ (top), $2^\circ$ (middle), $5^\circ$ (bottom). Solid and broken lines depict results for surface topology with peak and valley at the LE, respectively. Profiles on top of topology peaks terminate above the nominal geometry and those on top of valleys are truncated at the surface. Flow is from left to right. The velocity scale is indicated on plots with a horizontal black line.

C. Wake Measurements: Mean Centerline Velocity

For brevity, discussion of measurements in the wake of the cylinders at $\alpha = 0^\circ$ is limited to the streamwise evolution of the mean velocity along the wake centerline $\bar{U}_c$. Figure 11 depicts this evolution for cylinders with smooth and 2D-topology surface. Similar results are shown in Figure 12 to compare the two- and three-dimensional topology cases. Color assignment and line types are the same as in the previous figures. In the near-wake, $x/d < 4$, several features may be examined: the location and the strength of the reverse flow, the wake closure-length (i.e. the location where $\bar{U}_c/U_\infty = 0$), and the “wake recovery” (the rate of increase in $\bar{U}_c/U_\infty$ downstream of the closure length). Considering the reverse-flow magnitude, the maximum negative velocity is nearly the same for all cases, within the data scatter. The difference in the location of this maximum is barely distinguishable between the 2D and the 3D geometry, but for the smooth cylinder, this location is discernably displaced approximately $0.2d$ farther downstream. A similar difference is also seen in the closure length of the smooth cylinder relative to the cylinders with topology. For the latter the closure length is just over $0.75d$ from the trailing edge, while for the smooth cylinder it is about $0.2d$ longer. A more precise identification of the closure length by fitting and interpolating the data is not attempted in this work. Overall, the results indicate that the topology does not have a strong effect on the centerline-velocity features in the immediate near-wake.

The largest effect seen in Fig. 11 and Fig. 12 is that of the centerline velocity recovery for the cylinder with 2D topology with a peak at the LE. Between $2 < x/d < 4$, the recovery is slowest for this geometry. While there is no obvious reason as to why this should be the case, it is notable that the mean-velocity and $rms$ profiles over the cylinder surface for the 2D topology with peak at the LE deviate the most from all other cases at $\alpha = 0^\circ$ (see the top plot in
Fig. 5, 6, 9 and 10). In particular, the shear layer thickness implied from the profiles in the TE region of the cylinder with peak-leading topology is significantly larger than other cases.

![Graph](image1)

**Fig 11.** Comparison between the streamwise evolution of the mean centerline velocity in the wake of the cylinders with smooth surface (black line and symbols) and 2D surface topology (red lines and symbols) at $\alpha = 0^\circ$. Solid and broken lines are spline fits to the data and they depict results for surface topology with peak and valley at the LE, respectively.

![Graph](image2)

**Fig 12.** Comparison between the streamwise evolution of the mean centerline velocity in the wake of the cylinders with 2D (red lines and symbols) and 3D (blue lines and symbols) surface topology at $\alpha = 0^\circ$. Solid and broken lines are spline fits to the data and they depict results for surface topology with peak and valley at the LE, respectively.

Finally, in the far wake, all cases seem to lead to the same rate of centerline velocity recovery. However, the results for the smooth cylinder and that with 3D topology indicate a wake that is closer to the asymptotic state $\bar{U}_c/\bar{U}_\infty \rightarrow 1$.
than the cylinders with 2D topology. In addition, the streamwise evolution of $\overline{U}_c$ for 3D case is very close to the smooth cylinder, which is not the case for the 2D topology. It is not clear, though, to what extent the far-field evolution might be affected by blockage effects of the test section. This and other features of the wake evolution will be examined in more detail in future work by looking at the underlying mean and $rms$ velocity profiles and their various characteristics.

V. Conclusion

The effect of adding Fourier-synthesized surface topology to a rectangular cylinder with round corners, on the boundary layer and wake development around the cylinder is examined by breaking the problem complexity into two sub-problems. The first sub-problem involves surface topology variation along the cylinder’s perimeter only (2D mean flow), while the second one adds variation along the cylinder’s span (3D mean flow). This approach is expected to provide insight into the relative significance of the two- and the three-dimensional flow effects produced in these two sub-problems.

Results over a limited angle of attack range ($\alpha = 0^\circ, 2^\circ$ and $5^\circ$) show that the strongest influence of the topology on the boundary layer behavior is produced when the topology is associated with a peak at the cylinder’s leading edge (LE). In this case, a significantly thicker separation zone is produced and the separated shear layer is thicker, located farther away from the cylinder, and possesses the strongest unsteadiness, in comparison to the smooth cylinder and the cylinder section where a valley is present at the LE. These differences, however, become much less pronounced at the largest angle of attack, by the time the flow reaches the trailing edge.

Comparing results from the 2D and the 3D topology, differences in the flow behavior are predominantly seen at $\alpha = 0^\circ$ and $2^\circ$. For the geometry with a peak at the LE, the three-dimensionality does not alter the flow significantly until some distance downstream from the LE. This distance increases with increasing angle of attack such that at $\alpha = 5^\circ$, the difference in the mean and $rms$ velocity profiles for the 2D and the 3D topology are reasonably small. The latter observation is also found to hold when the geometry has a valley at the LE. This leads to the rather interesting finding that the 2D (“sectional”) flow behavior may provide a reasonable approximation of the 3D flow when the angle of attack is sufficiently large (within the range of $\alpha$ investigated in the present work).

Results from the wake measurements suggest that the maximum negative velocity is nearly the same for all cases. The location of this maximum and the closure point, however, are shifted upstream for the cylinders with 2D and 3D topology in comparison to the smooth cylinder. Considering the centerline velocity recovery rate, the cylinder with 2D topology with a peak at the LE is found to be the slowest, right after the closure point. It is seen in the boundary layer measurements, as mentioned above, that the shear layer thickness at the trailing edge of this cylinder is larger than the in other cases. Looking at this rate in the far wake, although the smooth cylinder and cylinders with 3D topology indicate a wake that is closer to the asymptotic state $\overline{U}_c/\overline{U}_{\infty} \to 1$, all cases seem to lead to the same rate of centerline velocity recovery. In addition, the streamwise evolution of $\overline{U}_c$ for the 3D case is very close to the smooth cylinder, which is not the case for the 2D topology.

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