TURBULENT PIPE FLOW RESPONSE TO ROUGH-TO-SMOOTH STEP CHANGE IN ROUGHNESS: FLOW STRUCTURE

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ABSTRACT
The response of a fully rough turbulent pipe flow ($Re_\tau = 9142$) to a step change in wall surface roughness (rough to smooth) is explored using pressure and particle image velocimetry measurements. We find that the pressure recovers relatively quickly downstream of the step ($x/D < 10$) though the mean velocity and shear stress distributions display an oscillatory response and are not fully recovered by the end of the measurement region ($x/D = 60$). The flow structure is explored through modal decomposition of the flow, where we see that downstream of the step the structures lose energy and move closer to the wall. Larger structures take longer to respond and display the strongest oscillatory response.

INTRODUCTION
Non-equilibrium, wall-bounded turbulent flows represent a subset of flow types that has not received sufficient attention, despite its prominent occurrence in applications. For example, rapid changes in surface condition can produce strongly out-of-equilibrium flows, and they are commonly encountered in flows over large vehicles or ship hulls especially at the junction of surface panels, flows through misaligned pipe sections, and in atmospheric flows over changing vegetation or water-land interfaces. Perturbed flows at high Reynolds numbers are of particular interest in many applications, and they are often beyond the reach of current turbulence models. By studying non-equilibrium turbulent flows, we hope to improve our ability to predict their behavior, and to uncover the principal governing mechanisms.

When wall-bounded turbulent flow is subject to a rapid change in surface condition, it can often result in long-lasting changes to the turbulent structure. For instance, in a study of a turbulent boundary layer subject to a short region of concave curvature, Smits *et al.* (1979) found an initial amplification of the Reynolds stresses followed by rapid decay to a level below the equilibrium levels, and the flow did not return to equilibrium by the most downstream location in the domain located 60 boundary layer thicknesses downstream. This non-monotonic response is due to the interaction between the turbulent shear stress and the mean shear, and it something that is not unique to flows with changes in curvature. A similar response was seen by Antonia & Luxton (1972) in a turbulent boundary layer subject to a step change in surface roughness (rough to smooth).

Here, we present an experimental study on the response of turbulent pipe flow at $Re_D = 131,000$ to a step change in surface roughness, specifically a transition from fully rough ($Re_\tau = 9142$) to smooth ($Re_\tau = 3035$). Primarily, we are concerned with the response of the turbulent structures to the step change in wall condition. We use modal decomposition methods to extract information about the response of the large, coherent structures that characterize wall-bounded turbulent flows. In the most related examples, Hellström *et al.* (2011) and Hellström & Smits (2014) showed that Fourier decomposition of the flow in the azimuthal direction coupled with proper orthogonal decomposition (POD) in the radial direction could be used in to identify the large energetic structures in turbulent pipe flow. We will make use of these tools to explore the impact of the change in surface condition on the structures downstream.

EXPERIMENTAL SETUP
The flow first developed in a smooth pipe for a distance of $120D$ downstream of the inlet (where D is the pipe diameter). Water was used as the working fluid. The flow then passed through a pipe roughened with sand grains, constructed similarly to that used by Nikuradse (1950), for a distance of $96D$. The equivalent sand grain roughness was $k_s = 415\mu$m, with $k^+ = k_s u_\tau/\nu = 66$. The flow then passed abruptly into a smooth pipe, where the flow response was measured. The bulk velocity was $U_b = 3.45$ m/s. The reference friction velocity was taken to be $u_\tau = 0.16$ m/s, corresponding to the fully developed smooth pipe friction factor at this Reynolds number. The Reynolds number based on the bulk velocity was $Re_D = 131,000$, and for the fully rough pipe $Re_\tau = 9142$, and for the smooth

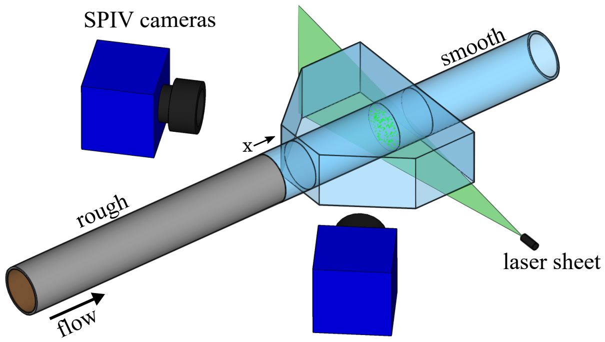

Figure 1. Schematic of the SPIV experimental setup.

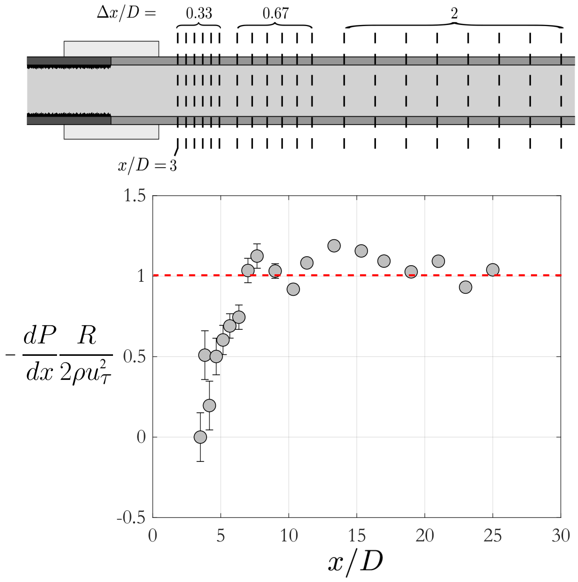

Figure 2. Pressure drop downstream of the step change in surface roughness. Schematic above plot indicates measurement locations, dashed red line represents the expected downstream equilibrium value.

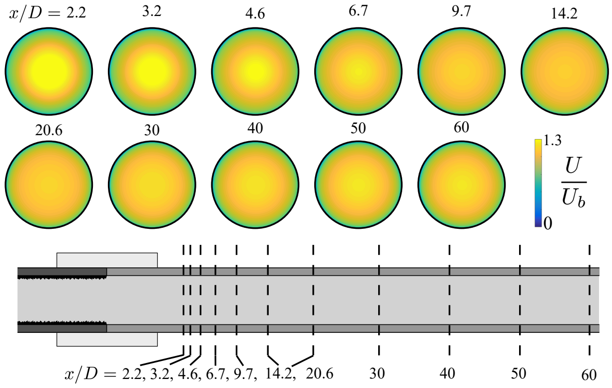

Figure 3. Contours of the mean velocity profiles downstream of the step change in roughness. Schematic below contours indicates measurement location.

pipe $Re_\tau = 3035$. A schematic of the experimental setup is shown in figure 1.

Stereoscopic particle image velocimetry (SPIV) measurements were taken at $x/D = 2.2$, 3.2, 4.6, 6.7, 9.7, 14.2, 20.6, 30, 40, 50, and 60 downstream of the step location ($x = 0$). Two 5.5 mega-pixel sCMOS cameras recorded images of a plane illuminated with a dual-pulsed 50 mJ Nd:YAG laser. The flow was seeded with 10 μm hollow glass spheres. A water-filled acrylic test section, designed such that the cameras and laser were normal to their respective acrylic walls, surrounded the glass pipe to minimize image distortion. A total of 11,000 images, acquired at a frequency of 25 Hz, were recorded at each downstream location. Pressure measurements were made at 20 locations between $x/D = 3$ and 25.

RESULTS

The development of the pressure gradient downstream of the step change is shown in figure 2. Initially, we see that dP/dx drops dramatically in response to the new boundary condition, but at $x = 10D$ the pressure gradient has approximately attained its downstream equilibrium value. There might be signs of a slight over-recovery, but the scatter in the data does not allow any firm conclusion. If it can be assumed that the pressure drop is the primary contributor to the force acting on the pipe walls, then this would indicate that the skin friction also recovers over about the same distance.

In contrast, the mean velocity distribution develops more slowly, and still has not achieved its equilibrium distribution by $x = 60D$, as shown in figure 3. The initially high velocity region near the center of the pipe redistributes downstream, overshoots its equilibrium profile, and then collects inwards to the center near the end of the measurement domain. A similar overshoot in the velocity distribution has been seen in other non-equilibrium flows, such as a boundary layer recovering from a short region of concave curvature (Smits *et al.*, 1979)). Despite being 60 diameters downstream we have not seen stabilization even in the mean flow.

The turbulence displays a similar overshoot. In figure 4 we show the Reynolds shear stress distributions at all downstream locations. The peak value occurs at $y/R = 0.35$ for the location nearest the step, and then decays from the wall-side towards the center which pushes the peak outwards. The profile gradually approaches the expected shape of a fully developed smooth pipe flow, but then overshoots that profile somewhere between $x/D = 9.7$ and 14.2. The shear stress levels remain trapped below the equilibrium levels, and they have not fully recovered even at $x/D = 60$.

To understand more fully the response of the turbulence structure to the step change in roughness, we will use modal deconstruction techniques: Fourier decomposition in the azimuthal direction, and Proper Orthogonal Decomposition (POD) in the radial direction. For the Fourier decomposition,

$$u(r,\theta,t) = \sum_{m=-\infty}^{\infty} \hat{u}_m(r,t) e^{im\theta}, \qquad (1)$$

where m is the Fourier mode number. Here, we reduce our measurements of the velocity field, which depend on the radial r and azimuthal θ direction as well as time t, to a summation of velocities that vary in r and t with an assumed form in the azimuthal direction. We can then organize the flow by mode number m and examine the energy contained in that mode.

Figure 5 (left column) shows contours of the energy as

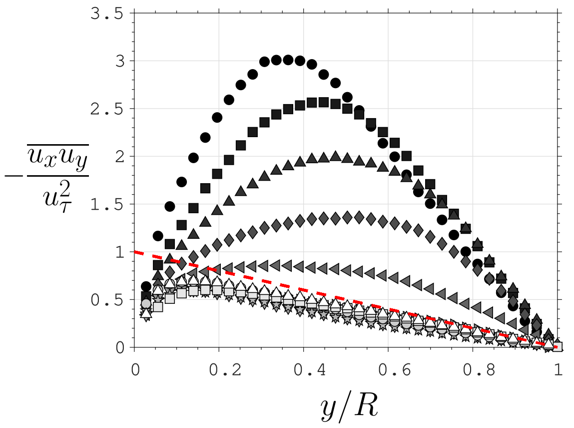

Figure 4. Reynolds shear stress profiles as they vary downstream from $x/D = 2.2 - 60$ colored black to white. The red dashed line indicates the expected slope of the curve in the outer layer for the fully developed equilibrium flow.

a function of y/R and m for multiple downstream locations. Downstream of the step change in roughness the energy in the lower modes ($m = 1$ to 10) decreases dramatically (the color is in log scale). Nearest to the step, the peak energy is away from the wall at $y/R \approx 0.3$ and is contained in $m = 2-3$; as we progress downstream the peak energy moves towards the wall and increases in mode number, indicating that structures are both getting smaller and lbecoming ess energetic.

Figure 5 (right column) shows the mode energy for $m = 1, 3, ...9$ (a-e) comparing all downstream locations. Here we see similar trends as with the contours—as the mode number increases (that is, the structures get smaller) the energy peaks move closer to the wall. Generally, the peaks for each mode decrease and move closer to the wall downstream; however in modes $m = 1-3$ the peak first moves away from the wall before then moving inward. In fact, $m = 1$ first increases in energy before decaying. This implies that modes lose energy starting at the wall moving inward, and the larger structures (lower modes) respond the slowest, which is not surprising.

We can further decompose the flow by applying POD to the radial direction, that is,

$$\hat{u}_m(r,t) = \sum_{n=1}^{\infty} c_{m,n}(t)\phi_{m,n}(r), \tag{2}$$

where the Fourier decomposed velocity ($\hat{u}$) is reduced to a summation of a product of separate functions of t and r. We expect that the radial mode shape ϕ is closely tied to physical features in the flow, as previously demonstrated by Hellström *et al.* (2011) and Hellström & Smits (2014). Figure 6 shows the downstream development of radial modes $n = 1$, 2 and 3 and azimuthal modes $m = 3$, 12, 30. Much like with the Fourier modes, we see that downstream flow structures are more concentrated near the wall, which is exaggerated in smaller structures (higher radial/azimuthal modes). For the lowest mode here ($m = 3$), the structures first move towards the wall then reverse direction, likely contributing to the second-order response of the mean velocity and shear stress, as seen in figures 3 and 4.

CONCLUSIONS

The response of turbulent pipe flow to a step change in surface roughness (rough to smooth) was explored using velocity and pressure measurements. The pressure, generally recovered quite quickly downstream, however the mean velocity and Reynolds shear stress were still showing signs of the step change up to $x/D = 60$. The response was second order, with an overshoot behavior seen in the profiles.

The coherent structure response was investigated through Fourier and proper orthogonal decomposition of the flow field to organize the flow into azimuthal and radial modes. Downstream of the step the structures became less energetic and moved closer to the wall, where larger structures (lower mode numbers) responded more slowly and sometimes displayed a similar second order response seen in the mean flow and shear stress distributions.

Similar second-order responses have been seen in the flow downstream of a short region of concave curvature and in a boundary layer recovering from a step change in roughness. These observations leave open the question of whether such a response may be characteristic of the response of wall-bounded turbulence to step changes in extra strain rates, and if this behavior could form the basis of a method of flow control.

ACKNOWLEDGMENTS

We gratefully acknowledge the support under ONR Grant "Understanding Turbulence on Navy Vehicles" N00014-17-1-2309 (Program Manager Joseph Gorski).

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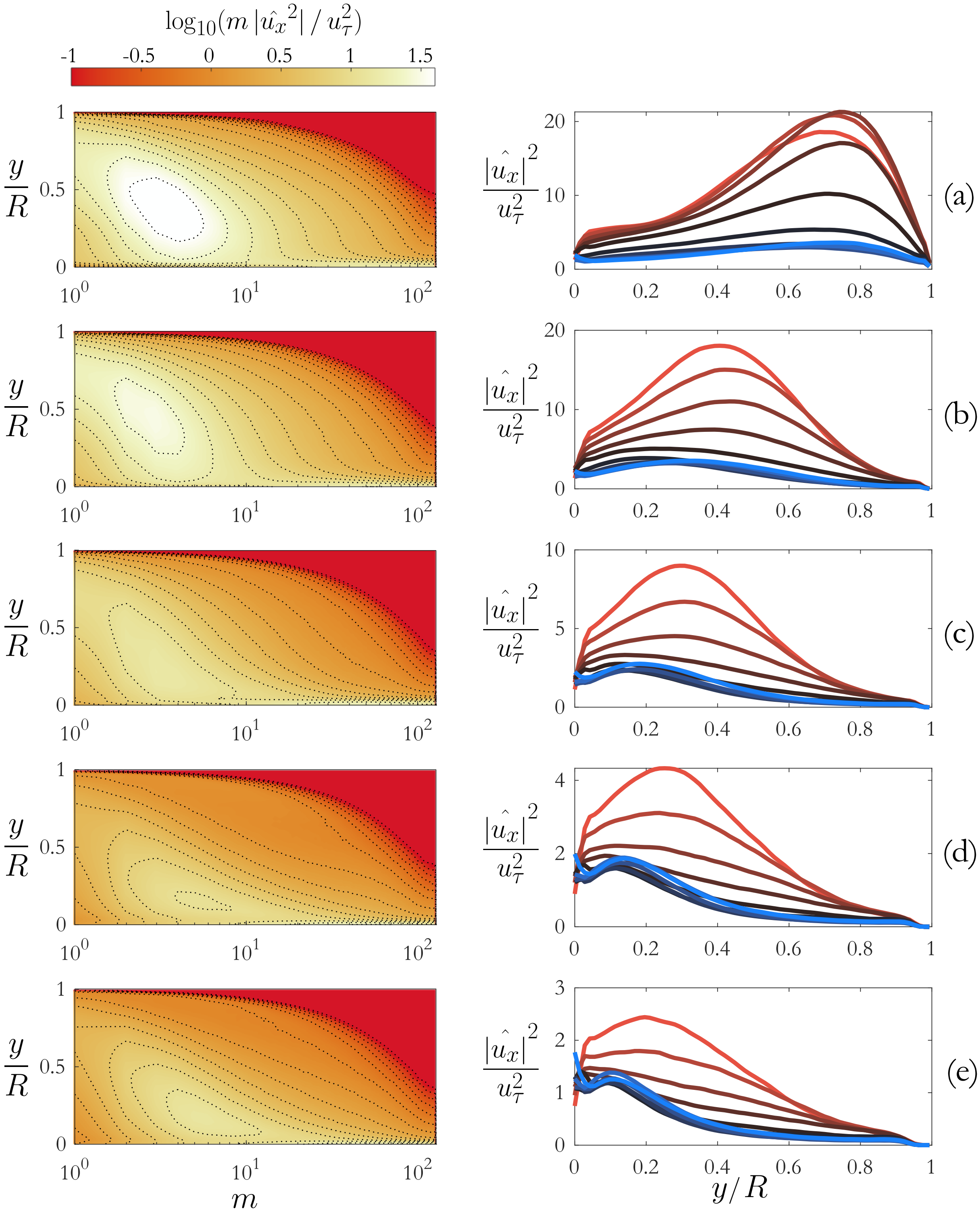

Figure 5. Left column: contours of the premultiplied streamwise velocity power spectral density for downstream locations $x/D = 2.2$, 4.6, 9.7, 20.6, 40 (a-e). Right column: Fourier decomposed velocity modes for $m = 1,3,...9$ (a-e) for all downstream locations $x/D = 2.2$-60 (red to blue line color).

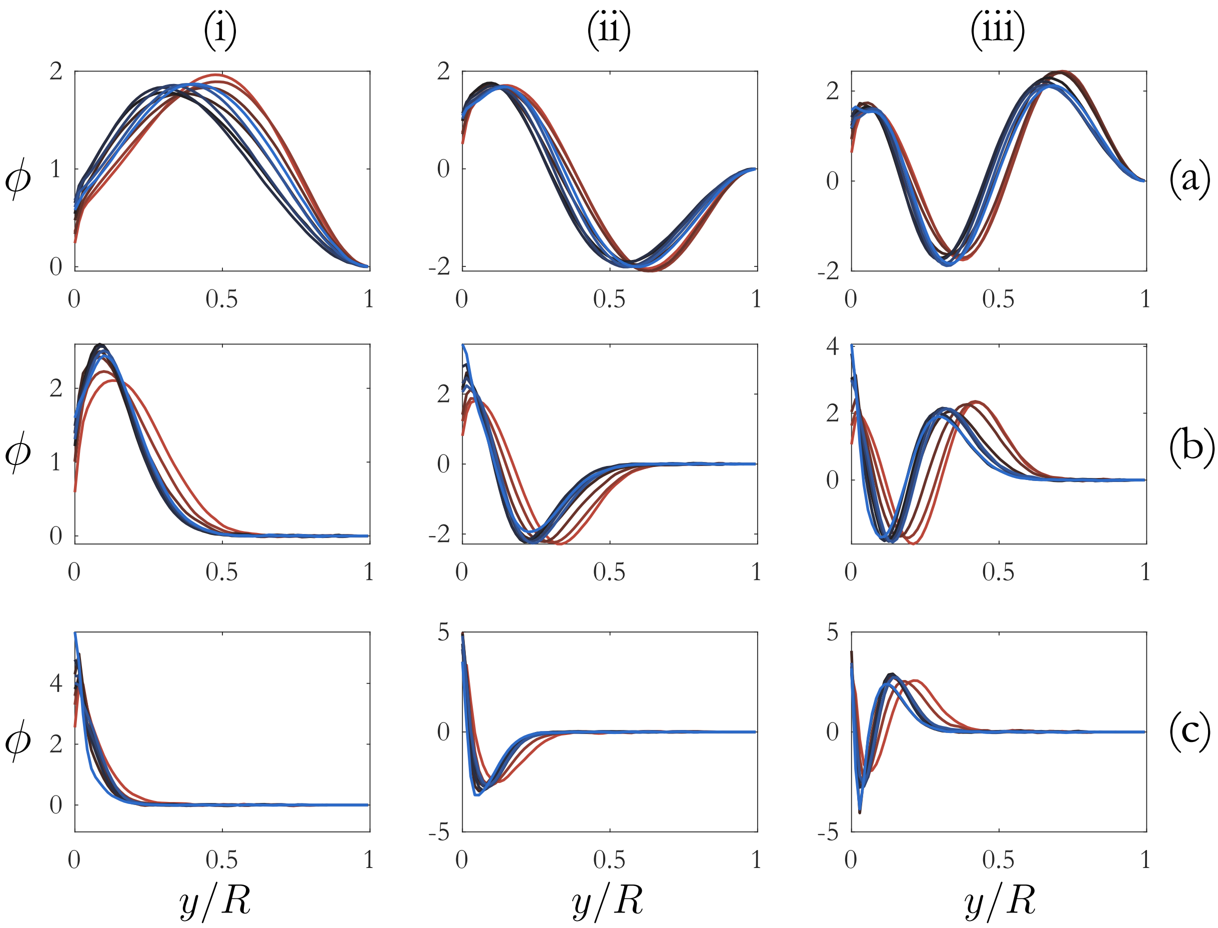

Figure 6. POD structure profiles for azimuthal modes $m = 3, 12, 30$ (a-c) and radial modes $n = 1$, 2 and 3 (i-iii). Downstream locations $x/D = 2.2 - 60$ colored red to blue.