Fundamental studies in turbulent flows:

We develop numerical, analytical and visualization tools to understand the fundamental physics of turbulent flows.

Our focus is to study flows specific to real life applications including:

(a) Atmospheric flows: We are interested in urban boundary layer over vegetation, man-made roughness. The studies are aimed at predicting (a) pollutant transport (b) strength of wake regions around roughness.

(b) Oceanic flows: Our interest is to understand the sediment transport and mixing process over rough bed-forms.

(c) Physiological flows: We are interested in obtaining flow dependent metrics in stenosed coronary artery to characterize the disease.

(d) Energy related Wind turbines: We are interested to understand the fundamental physics due to the (a) rotation of the blades, (b) effect of the tower height, (c) wake-wake interactions in wind turbine cluster.

The tools that we develop:

1. Direct numerical simulations tools (DNS): Large scale DNS tools are developed to conduct fundamental studies of flow dynamics.

2. Analytical tools:
   (a) Proper orthogonal decomposition (POD) tools are developed to study and spatial and time events of rough-walls.
   (b) Novel transport equations for rough wall: A unique set of decomposition is proposed based on multiphase concept to analyze the rough-wall data. An alternate set of transport equations for mass, momentum and energy are derived. These alternate set of equations have explicit roughness production and roughness drag terms which are not present in classical Reynolds transport equations.
   (c) Statistical tools for the classification of random roughness.

3. Flow visualization tools: Turbulence is characterized by large-scale organized patterns and range of length scales. Flow visualization is an effective way to understand the mechanisms as well as flow patterns. We develop a range of such tools.

The following are the details:

Understanding flow dynamics due to surface roughness: Surface roughness is a defining feature of many of the high Reynolds-numbers flows found in engineering. In fact, the higher the Reynolds number (Re), the more likely the effects of roughness are significant, since the size of the roughness elements becomes increasingly large compared to the near-surface viscous length appropriate for smooth-wall flows. As a result, turbulent boundary layers over the hulls of ships and submarines, within turbo-machinery, and over the surface of the earth are all cases to which the smooth-wall idealization
rarely applies. Unfortunately the impact of surface roughness is not entirely understood, and a number of important fundamental questions have not yet received a satisfactory answer.

(a) Flow over rough-wall turbulent boundary layers:

We use DNS as a tool to address the following fundamental questions that arise, which we attempt to answer for one type of representative roughness, are: (1) What is the height of the roughness sublayer and how does it compare to the other length scales of the roughness? (2) What is the significance of the roughness sublayer with respect to the dynamics of turbulence in this region? (3) Are the turbulent statistics in the logarithmic region independent of the flow in the roughness sublayer? and if not, (4) How do the turbulence structures generated within the sublayer interact and determine the eddy structure in the log region?

What is the significance of the roughness sublayer with respect to the dynamics of turbulence in this region? (3) Are the turbulent statistics in the logarithmic region independent of the flow in the roughness sublayer? and if not, (4) How do the turbulence structures generated within the sublayer interact and determine the eddy structure in the log region?

We next investigate the nature of pressure fluctuations induced by surface roughness in a turbulent channel flow at $\text{Re}_\tau=400$. The regular three-dimensional periodic roughness elements, whose peaks overlap approximately 25\% of the logarithmic layer, The three-dimensional roughness elements alter the pressure statistics significantly, compared to the corresponding smooth-wall flow, in both the inner and outer (core) regions of the channel. The direct consequence of roughness is an increased form drag, associated with more intense pressure fluctuations, however, it also tends to alter the pressure fluctuations in the outer-layer
of the boundary layer, as well, as represented by altered length scales obtained from the two-point pressure-pressure correlations. We also find that the depth of the roughness sublayer defined by the pressure fluctuations is very different from that given by the large- and small-scale statistics from the velocity field. This paper is an important step towards establishing the significance of pressure statistics along with velocity statistics in demonstrating that roughness modifies the outer-layer.

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(b) Unsteady flow dynamics over rough-wall: A fundamental study has been performed to understand alterations in the turbulence statistics due to unsteady forcing for flows over rough-walls in a channel using direct numerical simulation (DNS). Pulsatile flow (combination of current and wave) has been generated by applying an unsteady non-zero mean forcing in the form of time varying pressure gradient such that the amplitude of the oscillations is between $19\%-26\%$ of the centerline mean velocity. The analysis has revealed DNS of quasi-steady flow in channel with rough walls can represent the long-time averaged mean and turbulence statistics of unsteady flow accurately. The non-dimensional stokes length ($l_s^+$) serves as an appropriate parameter to classify the flows into high, intermediate and low forcing frequency regimes even for a rough wall. For the high frequency forcing, unsteadiness alters the mean and turbulence only in the inner layer with the turbulence intensities being out of phase with each other and also with Reynolds stress as well as centerline mean velocity. For the intermediate frequency forcing, unsteadiness modifies mean and turbulence beyond the inner layer. In the inner layer the turbulence intensities are out of phase with other. The Reynolds stress and the centerline mean velocity are in phase with each other in the inner layer, but they becomes out of phase in the outer layer. For the low frequency forcing, in the inner as well as the outer layer the mean velocity and turbulence intensities are significantly altered due to unsteadiness. The turbulence intensities and Reynolds stress are in phase with each other and also with centerline mean velocity.

(c) Proper Orthogonal decomposition to understand surface roughness. Snapshot proper orthogonal decomposition (POD) is used investigate the effect of three-dimensional surface roughness effects in a turbulent channel flow. Direct numerical simulations of turbulent channel flow with rough-walls is used to extract POD modes. 1D POD analysis in wall-normal direction has revealed that convergence of the POD for a rough-wall is slower compared to the smooth-wall. A length scale to represent the extent of inhomogeneity for the rough-wall has been determined based on the POD modes at the $\text{peak}$ and $\text{valley}$-locations of the roughness. On analysis of two-dimensional POD (in $y-z$ and $x-y$ planes) has revealed that roughness alters the size and spacing of the coherent structures.
Next we quantify the time-events that contribute to the dynamics of wall-bounded flows with rough walls. Lumley's Proper Orthogonal Decomposition (POD) methodology has been used to extract the energetic modes of the flow. We have used the concept of entropy, a representation of lack of organization in the flow, to represent the extent of spread of turbulent kinetic energy to higher modes. The rough wall dynamics is dominated by fast activity (short time period) \( \text{\it propagating modes} \) and slow activity (long time period) \( \text{\it roll modes} \). A single dominant time scale has been captured for all the propagating modes in flows over smooth walls; multiple dominant time scales representing various vortex shedding events are captured for rough walls. Variable-interval time averaging technique (VITA) has been used to obtain the bursting frequency. The bursting frequency of rough wall turbulence is higher compared to smooth wall turbulence suggesting roughness enhances turbulence production activity. Another insightful observation for rough walls revealed by our study is the vortex shedding frequency of roughness elements is much higher compared to the bursting frequency of rough wall turbulence. POD provides a straightforward method to extract the natural frequency of shed vortices due to roughness, an important dynamical activity in rough wall turbulent boundary layers.

Novel balance equations for analysis of roughness: The starting point for analyzing the various sources of the turbulence physics are the mean transport equations. However, the time-averaged Navier-Stokes (RANS) equations for the rough wall will not contain the roughness drag term and tells us little about the effects of roughness. Hence an alternate form of RANS is required which can elucidate the roughness physics. Another issue with RANS equations for rough wall turbulent flows is that the spatial variance of roughness prevents averaging in planes parallel to the boundary.

The main goal of this research is to demonstrate novel analytical tools specifically suitable for rough-wall flows. For this purpose the traditional Reynolds decomposition of flow variables is modified to unique velocity decomposition consisting of three components (three-level decomposition). Further, 2-phase (solid-liquid) spatial and temporal averaging strategy directly applicable to solid roughness is proposed. The exact and fundamental transport equations (momentum, energy, turbulent stress) for 2-phase formulation will explicitly contain the roughness terms such as mean boundary drag and production of turbulence by roughness. These transport equations for the above three components will facilitate to establish and understand the local interactions of the energy and stress of the mean flow, the turbulence and wall roughness.
(e) UNDERSTANDING THE TURBULENT FLOW OVER ROUGH SURFACES WITH IDEALIZED AND RANDOM ROUGHNESS ELEMENTS

Flows over random roughness are the least understood, but most accurate when it comes to modeling natural environments. Some of their many applications include oceanic or fluvial sea beds, atmospheric flows over urban areas (buildings), or engineering surfaces with build-up or erosion. Realistic roughness not only takes into account variations in spacing, but also in roughness height as well.

Understanding the physics of turbulent flows over rough surfaces is of significant consequence in natural systems such as coastal and environmental flows, where surface roughness is more of a rule than an exception. In most of these natural systems, e.g. bedforms found on the ocean floor, the roughness elements are mostly random in nature, either in their distribution or geometry. As of now, we do not have an understanding of how the turbulent flow is altered due to the presence of random roughness. The focus of this work is to understand the differences between random and idealized roughness element for three-dimensional roughness geometries specific to bedforms on ocean floors. Flow over ripple-shaped roughness is of significant importance due to their occurrence in natural environments such as coastal regions and their influence on topics such as sediment transport and surface wave dissipation. Ripple profiles are generally characterized by a sinusoidal or parabolic shape, height, and wavelength (spacing, or distance between peaks).

This research seeks to provide a better understanding of flow over idealized and random rippled surfaces. It seeks to clarify the classification of non-rib-style roughness elements, as well as further the understanding of flow over idealized three-dimensional ripples. Additionally, classification of random roughness and their effect on the flow is investigated. The following chapter provides the methodology for conducting the simulations, including the generation of ideal and random surfaces. It also describes multiple ways of characterizing the rough surfaces. The rest of the thesis contains results of simulations over three-dimensional ideal and random rough surfaces, followed by a comparison between the two.