TOWARDS A SIMPLIFIED PRACTICAL MODEL FOR THE SIMULATION OF TURBULENT FLOWS OVER ROUGH SURFACES

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A detailed understanding of fire behaviour is required to manage fire safely and effectively. Fire behaviour depends on a range of factors including the fuel type, fuel quantity, fuel moisture content, topography and ambient weather conditions, especially wind speed. Wind speed profile (the variation in wind speed with respect to distance from the ground) is strongly influenced by topography. For atmospheric flow, the topography is often modelled as a rough surface which promotes the generation of turbulence and offers greater resistance to the wind flow near the earth's surface. As a result the topography affects the rate of spread of a fire and therefore its intensity. Higher wind speeds tilt the flames forward to pre-heat the fuel ahead of the fire and push the fire along increasing the rate of spread. Understanding how wind speed changes as it passes over grasslands or forests is therefore crucial to developing better fire behaviour predictions in support of firefighting agencies.

Computing the exact physics of turbulent fluctuating flow over grasslands, forests and canopies is a very expensive and resource intensive process. Scientists need to use complicated mathematical models and state of the art sophisticated computational algorithms many thousands of CPU hours on the largest supercomputers. It is not feasible for practitioners to resort to powerful computers in order to account for roughness in order to calculate the profile of the wind as it flows over forests and urban landscapes. Instead practitioners seek some simple mathematical parameterisation that captures the main dynamics of velocity fluctuations near the rough wall. For example, parameterisations of the near wall velocity over forests are required for numerical weather prediction.

(a) (b)

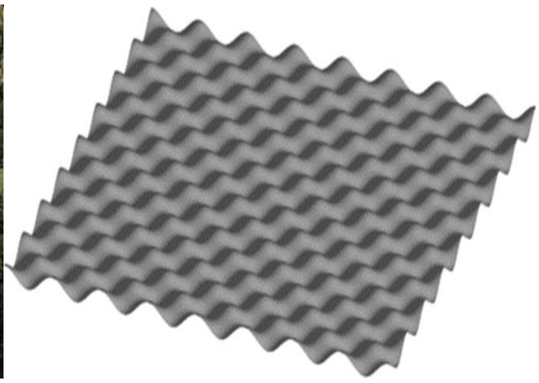

Figure 1. A forest (a) can be treated as a rough surface, but for modelling purposes that can be idealised as shown in (b). In the limit the undulations can become needle-like so that they simulate the behaviour of trees.

Due to the fact that the turbulent flow over real-world rough surfaces can get overly complex and mask the pertinent physics, we have chosen to concentrate our efforts in understanding the flow over an idealised sinusoidal surface. Figure 1 compares a forest to the idealised surface used in this study. The following discussion is an extract from a paper published in the Journal of Fluid Mechanics (MacDonald et al., 2016).

The velocity profile of the wind flowing over smooth surfaces is very well established, but for practical applications, we need to know the velocity profile over rough surfaces. Roughness is characterised by the solidity (Λ) of the roughness. Generally speaking, solidity is the frontal area of the roughness elements which are exposed to the wind. If the solidity is low the roughness is called sparse, and if the solidity is high, the roughness is dense.

The sparse and dense regimes of roughness were investigated using direct numerical simulations of the flow over three-dimensional sinusoidal roughness. The minimal-span channel technique, recently used by Chung et al. (2015) for rough-wall flows, was used. A minimal-span channel consists of a channel which is one-roughness element wide. Minimal-span channels are much cheaper to compute compared with s which is many roughness elements wide. This study shows from the analysis of second-order turbulence statistics that the root-mean-square streamwise and wall-normal velocity fluctuations can beaccurately captured by the minimal-span channel simulations, especially within the roughness crest for rough-wall flows.

The dense regime of roughness was found to occur when the solidity was greater than approximately 0.15. In this regime, the velocity fluctuations within the roughness elements decreased, although were not negligible even for the densest case. The limit as solidity tends to infinity appears to correspond to a smooth wall in which the wall was located at the crest of the elements, and second order statistics did show the dense roughness cases were tending towards this limit.

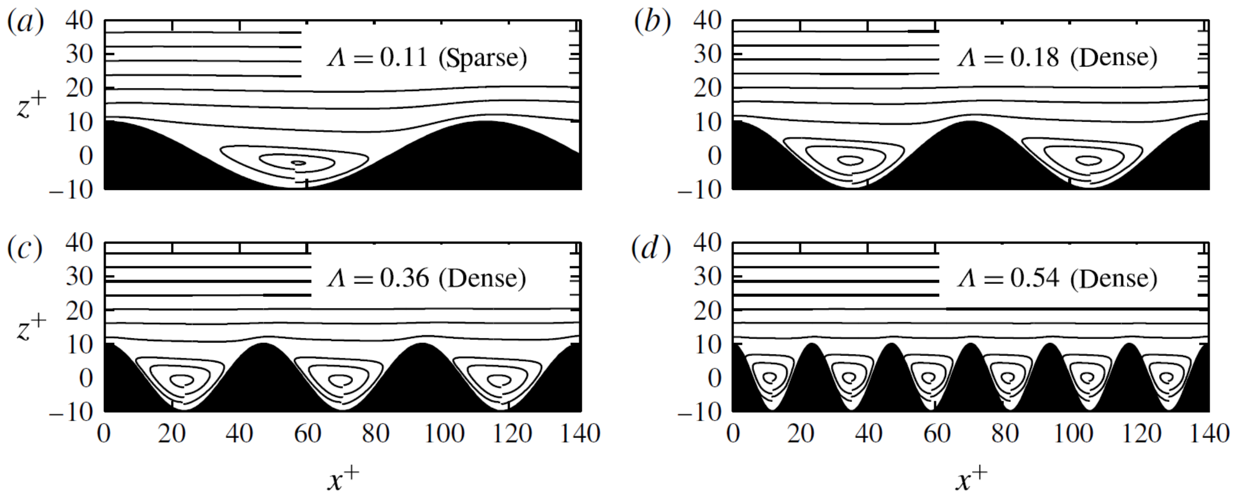

Figure 2. Mean streamlines over roughness of various solidity, in the streamwise–wall-normal plane. Flow is in (a) sparse and (b–d) dense regimes.

Conceptual models of the dense regime of roughness often describe stable vortices within the roughness elements, with high-speed fluid skimming over the top of the roughness. The sparse regime, meanwhile, is described by a much smaller recirculation zone with respect to the roughness crest, with the separation point being closer to the reattachment point. In order to assess the veracity of these descriptions, the mean streamlines are shown in figure 2 for both sparse and dense roughness. All four sets of streamlines show an almost identical flow pattern, with the recirculation region appearing similar in terms of the roughness wavelength. The area of flow recirculation, A_R, does scale with solidity according to A_R/A_T ≈0.18 log (Λ)+0.9, where A_T is the total area occupied by fluid below the roughness crest; however, there does not appear to be a distinct change in flow structure between the sparse (figure 9a) and dense (figure 9b–d) regimes. It is clear that these qualitative descriptions of roughness are not adequate on their own to indicate existence of the dense regime, or to explain why a slightly different flow pattern results in a reduction in the roughness function.

Figure 3(a) shows the mean velocity profile for the smooth wall (Λ=0) and a sparse regime case (Λ =0.11). It can be observed that roughness reduces the velocity profile. On the other hand, from figure 10 (b), it can be observed that beyond wall unit z+> 20, velocity profile over dense rough wall rises above the velocity profile over sparse rough wall and it increases with Λ.

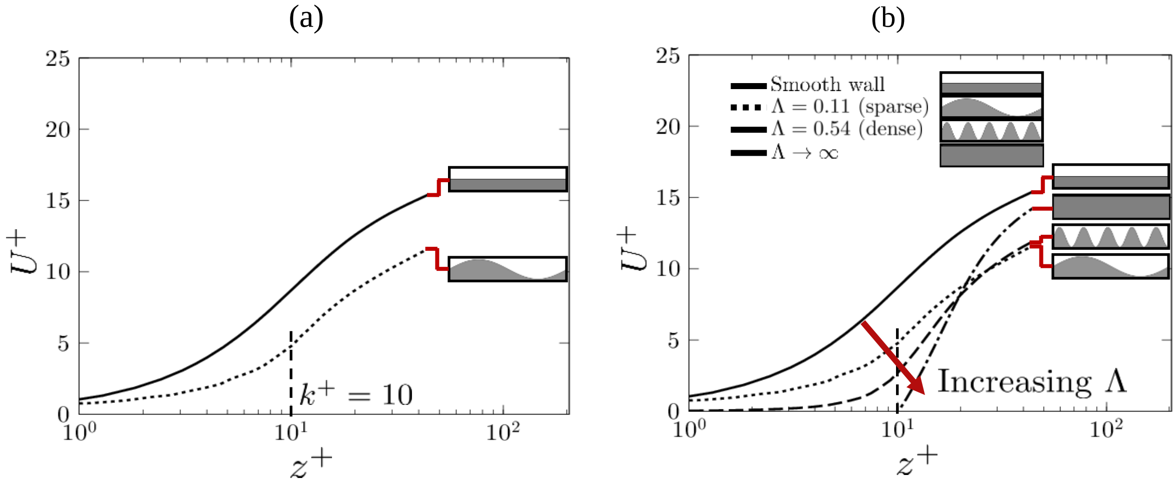

Figure 3. Mean velocity profile (a) Comparison of smooth wall with sparse roughness and (b) Comparison of smooth wall with rough wall with increasing solidity (includes both sparse and dense roughness).

An analysis of the mean momentum balance enabled the roughness function to be decomposed into two contributions. This revealed that the primary reason for the reduction in the roughness function that is seen in the dense regime is due to the reduction in Reynolds shear stress above the roughness elements. The near-wall cycle, located at $z^+ \sim 15$ for a smooth-wall flow, is pushed up above the roughness elements. As the solidity increases the location of the near wall cycle also increases. In the infinite solidity limit, the rough wall effectively becomes a smooth wall located at the roughness height k^+, and therefore the near-wall cycle is located at $z^+ \sim k^+$ plus 15 wall units. Spectral analysis indicates that the dense regime gradually reduces energy in the long streamwise length scales that reside close to the roughness elements. As the density increases, the long streamwise length scales are increasingly damped and the near-wall cycle is pushed up away from the wall.

From the above study simple equations can be derived for the difference in the velocity profiles as a function of roughness. By choosing the appropriate dimensions of the surface tree-like objects, the velocity profile can be accurately calculated. This can be useful for atmospheric boundary layer modelling.

References:

MacDonald, M., Chan, L., Chung, D., Hutchins, N. and Ooi, A., 2016. Turbulent flow over transitionally rough surfaces with varying roughness densities. *Journal of Fluid Mechanics*, *804*, pp.130-161.

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