Turbulent flows over sparse canopies

Akshath Sharma and Ricardo García-Mayoral
Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, UK
E-mail: r.gmayoral@eng.cam.ac.uk

Abstract.

Turbulent flows over sparse and dense canopies exerting a similar drag force on the flow are investigated using Direct Numerical Simulations. The dense canopies are modelled using a homogeneous drag force, while for the sparse canopy, the geometry of the canopy elements is represented. It is found that on using the friction velocity based on the local shear at each height, the streamwise velocity fluctuations and the Reynolds stress within the sparse canopy are similar to those from a comparable smooth-wall case. In addition, when scaled with the local friction velocity, the intensity of the off-wall peak in the streamwise vorticity for sparse canopies also recovers a value similar to a smooth-wall. This indicates that the sparse canopy does not significantly disturb the near-wall turbulence cycle, but causes its rescaling to an intensity consistent with a lower friction velocity within the canopy. In comparison, the dense canopy is found to have a higher damping effect on the turbulent fluctuations. For the case of the sparse canopy, a peak in the spectral energy density of the wall-normal velocity, and Reynolds stress is observed, which may indicate the formation of Kelvin–Helmholtz-like instabilities. It is also found that a sparse canopy is better modelled by a homogeneous drag applied on the mean flow alone, and not the turbulent fluctuations.

1. Introduction

The study of flows over canopies has been a topic of interest for over five decades. Inoue [1] was one of the first to study the coherent bending of canopies on windy days and termed it “honami”. Some early experimental studies, notably Finnigan & Mulhearn [2], attributed this coherent bending to energetic gusts of air from the outer region of the atmospheric boundary layer. Raupach et al. [3] provided an alternate explanation for this phenomenon, theorising that a Kelvin–Helmholtz-like instability stemming from the inflection point in the mean velocity profile was responsible for the coherent motion of the crops. Since then, a large number of studies, summarised in [4, 5], have reported the formation of Kelvin–Helmholtz-like instabilities over canopies. The characteristic length scales of these instabilities is set by the shear length scale, \( L_s = U/(dU/dy) \) at the canopy tips [4, 3]. Hence, by manipulating the shear length of a canopy it could be tuned to produce these instabilities at a particular scale, thereby providing a method to alter and possibly control these scales in a turbulent flow. This could potentially be used to design artificial canopies to harvest energy, enhance heat transfer, or alternatively, natural canopies to reduce crop loss [6].

Although Kelvin–Helmholtz-like instabilities are known to be spanwise coherent, in some cases they have been known to become distorted after their formation in turbulent flows. Finnigan et al. [7] and more recently, Bailey & Stoll [8] performed Large-Eddy Simulations of flow over dense canopies to determine the evolution of the Kelvin–Helmholtz rollers over the canopy.
Finnigan et al. [7] proposed a model which involved the pairing of adjacent rollers to form large hairpin-like structures over the canopy. Bailey & Stoll [8] tried to establish how persistent the two-dimensional structures were after their formation, in the background turbulence. They argued that while hairpin structures of scales smaller than the Kelvin–Helmholtz rollers were present for their case, the overall two dimensional structure of the rollers was preserved in the developed flow. They also found that these rollers are responsible for the majority of the Reynolds stress near the canopy top.

All the above studies involved dense canopies, where the canopy could be modelled as a homogeneous drag force. As the spacing between canopy elements is increased, the homogeneous assumption eventually fails, leading up to the regime of sparse canopies. Such canopies are harder to characterise as there is no clear definition for the limit of canopy density where it can be called sparse. Based on empirical evidence, Nepf [5] defined a sparse canopy as one in which the ratio of frontal area of the canopy elements to the base area is $\lambda_f \leq 0.1$. Depending upon the level of sparsity, Kelvin–Helmholtz rollers have been reported over sparse canopies as well [9, 10], although there is no defined limit of sparsity till which the rollers can be sustained.

In the present study, we explore the use of a sparse canopy to manipulate large scales in a turbulent flow, while attempting not to affect the smaller scales. For this purpose, we simulate the flow over a canopy in which the spacing between the canopy elements is larger than the width of streaks. This should limit the effect of the canopy on the near-wall turbulence cycle, while also reducing its impact on smaller scales. In order to target the larger scales within the flow, the height of the canopy is kept relatively large so that the tips of the canopy elements protrude into the base of the logarithmic layer. The shear layer thickness at the canopy top, which controls the wavelength of the instabilities formed, is tuned by adjusting the profile of the drag force applied by the canopy in the vertical direction. This should theoretically allow us to control the scale of the instability being introduced into the flow. The canopy geometry and the distribution of drag force is discussed further in the next section. The drag force applied by the canopy also controls the strength of the inflection point in the mean velocity profile. Higher inflection generally results in a stronger instability, but, too large a drag can also damp the instability [11].

In addition to representing the individual canopy elements, we also explore whether a
Table 1. Simulation parameters. $u_\tau$ is the friction velocity based on the total drag in the channel, $\delta^+$ is the Reynolds number based on $u_\tau$, $h^+$ is the height of the canopy, $N_c$ and $\int D_y^+$ are the number of canopy elements and the drag force integrated over the canopy height. $\Delta x^+$, $\Delta z^+$ and $\Delta y^+$ are the resolutions in the streamwise, spanwise and wall-normal directions respectively.

| Case | $u_\tau$  | $\delta^+$ | $h^+$  | $\int D_y^+$ | $\Delta x^+$  | $\Delta z^+$ | $\Delta y^+$ |
|------|-----------|------------|--------|--------------|----------------|---------|-----------|
| S    | 0.1363    | 504.3      | 105.9  | 16 $\times$ 8 | 0.809          | 8.25    | 4.12      | 0.20-2.0 |
| H    | 0.1363    | 504.3      | 105.9  | $-$          | 0.849          | 11.00   | 5.50      | 0.20-2.0 |
| H0   | 0.1405    | 520.5      | 109.3  | $-$          | 0.823          | 11.36   | 5.68      | 0.21-2.1 |

homogeneous drag can be used to approximate the flow within sparse canopies. For this purpose, the flow in two more canopies is simulated, one exerting a homogeneous drag on the flow as in [8, 12, 13, 7], and the other only exerting drag on the mean flow and not on the fluctuations, that is, only on the zero mode in Fourier space. The drag of these canopies is set to exert roughly the same total drag on the flow as the sparse one.

The organisation of the paper is as follows. Section 2 briefly describes the numerical method used, and also elaborates on the canopy geometry. Section 3 discusses the results obtained from the simulations conducted before presenting the conclusions and summary in section 4.

2. Numerical simulations

The simulations are conducted in an open channel with the canopy elements protruding upwards from the wall. The streamwise, wall-normal and spanwise coordinates are $x$, $y$ and $z$ respectively, with the associated velocities being $u$, $v$ and $w$. The size of the simulation box is $2\pi \times 1 \times \pi$, with reference to the channel height, $\delta = 1$. The domain is periodic in the $x$ and $z$ directions. A schematic representation of the numerical domain for the present study is shown in figure 1. No-slip and impermeability conditions are applied at the bottom boundary along with free slip and impermeability conditions at the top. The flow is incompressible, with the density set to one for convenience. The numerical method used to solve the three dimensional Navier-Stokes equations is adapted from [14]. The streamwise and spanwise directions are decomposed using a Fourier spectral discretisation. The wall-normal direction is discretised using a second order centred difference scheme on a staggered grid. The grid in the wall normal direction is stretched to give a resolution ranging from $\Delta y_{\text{min}} \approx 0.2$ to $\Delta y_{\text{max}} \approx 2$. The time advancement is carried out using a three-step Runge–Kutta method [15], with continuity enforced using a fractional-step, pressure-correction method [16].

To simulate flow in sparse canopies the individual canopy elements need to be resolved. This is usually achieved by the means of an immersed boundary method, where a body force is applied opposing the flow within the roughness or canopy elements [17, 18]. In the present work, an ‘immersed forcing’ approach similar to that used by [9] is used to represent the individual canopy elements. It differs from the traditional immersed boundary method in the sense that the velocity within these boundaries is not strictly zero.

For the sparse canopy, case S, a forcing of the form $C_d|u|$, where $C_d$ is the drag coefficient, is applied opposing the direction of flow at the points representing the canopy elements. This is similar to the method employed by [9] to represent sparse, but row-homogeneous canopies. In the present case, the canopy elements can be thought to be made from a porous material, which while allowing some fluid to pass though it, imparts a large drag force on the flow. For the first dense canopy, case H, a homogeneous forcing of the form $C_d|u|$ is applied to all points below
Figure 2. (a) The balance of total stress in the channel scaled with $u_\tau$. ——— represents case S; - - - - case H; ····· case H0. The blue, orange, purple and green lines represent the total stress, Reynolds stress, cumulative canopy drag and viscous stress respectively. (b) The Reynolds stresses and viscous stresses rescaled by $u^*$. The solid black lines represent a smooth channel. The vertical dashed line depicts the height of the canopy.

the height of the canopy. In the last simulation, case H0, a forcing of form $C_d\langle u \rangle^2$ is applied to all points below the height of the canopy. Note that in case H0, the drag is only applied in the streamwise direction and has no fluctuating component. Case S was run first at a constant mass flow rate, with the viscosity adjusted to get the target friction Reynolds number. The subsequent cases were also run at the same mass flow rate, with the drag coefficients, $C_d$, adjusted to obtain similar mean pressure gradients as case S. The relevant parameters for each simulation are given in table 1. In order to tune the shear layer thickness, the head of the canopy, i.e. approximately the top 20 wall units, has a larger frontal area, and consequently exerts a larger drag force than the rest of the canopy. This causes a local increase in shear at the head of the canopy, as can be observed in figure 2, which in turn sets the shear layer thickness at the canopy top. Consequently, it should also set the wavelength of the Kelvin–Helmholtz-like instability formed over the canopy. For case S, the canopy elements are in a square arrangement, and the spacing between the elements is $\Delta x_f^+ \approx 200$. This results in a roughness density of $\lambda_f = 0.075$, which is within the sparse range empirically demarcated by [5]. In addition, the spanwise spacing between the canopy elements is roughly twice the width of streaks near the wall, implying that the canopy is sparse even from the point of turbulent fluctuations.

The data for the smooth wall was obtained from the simulation of a full channel at $Re_\tau = 550$ [19].

3. Results and discussion
The balance of stresses in the channel is shown in figure 2a, and can be written as
Figure 3. Mean velocity profiles, (a) scaled in outer units, (b) scaled in deficit law in inner units. The black, red, purple and blue lines represent smooth-wall, S, H0 and H respectively. The dashed line marks the canopy top.

\[
\frac{dP}{dx} + \tau_0 + \int_0^h D_y dy = -\bar{u}^+\bar{v}^+ + \frac{1}{Re} \frac{dU}{dy} + \int_y^h D_y dy,
\]

\[
D_y = \begin{cases} 
C_d(y)|U|, & \text{for } y \leq h \\
0, & \text{for } y > h 
\end{cases}
\]

where \(C_d(y)\) is the drag coefficient of the canopy, \(\tau_0\) is the wall shear stress, \(-\bar{u}^+\bar{v}^+\) is the Reynolds stress, \(h\) is the height of the canopy, and \(U\) and \(dP/dx\) are the mean streamwise velocity and mean pressure gradient respectively.

For a smooth channel in equilibrium, this balance essentially reduces to the mean pressure gradient countering the shear stress at the wall, and the friction velocity can be defined as

\[
u^2 = -\delta \frac{dP}{dx}.
\]

In the present case, we define a ‘global’ friction velocity using equation (1). This formulation takes into account the wall shear stress and the total drag exerted by the canopies. All quantities in figure 2a are normalised by this ‘global’ friction velocity, \(u_\tau\). However, unlike the wall shear stress, the drag force has a vertical distribution, and the flow within the canopy at a given height feels the influence of the wall shear stress and a contribution of the drag up to that height. Tuerke & Jimenez [20] observed that, when the pressure gradient has to balance body forces additional to the wall shear stress in the channel, the turbulent fluctuations scale with the local shear at a given height instead of just the wall shear. They calculated the local friction velocity, \(u^*\) corresponding to the local shear as

\[
u^*(y) = \left( \frac{\delta \tau_l}{\delta - y} \right)^{1/2},
\]
where the local shear is the sum of the viscous and Reynolds stresses at a particular height, 
\[ \tau_l = -u'v' + \frac{1}{Re} \frac{dU}{dy}. \]

Figure 2b depicts the Reynolds and viscous stresses within the channel, renormalised by \( u^* \). The resemblance of these renormalised stresses to the smooth wall data seems to suggest that the major affect of the addition of the canopy in the channel is the rescaling of the turbulent fluctuations. However, we will see later that this is not the case. It can also be observed that even after the rescaling, the Reynolds stresses in the dense canopies, cases H0 and H, are more damped than in case S. Although not unexpected, the drag damping in case H affects the turbulence structures within and outside it more than that for cases H0 and S.

The differences manifest themselves in the mean velocity profiles as well, as can be observed in figure 3. The maximum velocity within the dense canopies, H and H0, are larger than that in the sparse canopy, S. The likely factor behind this is the formation of wakes and regions of flow separation in case S, which are absent in the other cases. The wakes can be observed in the contours of streamwise velocity shown in figure 3. Other differences may be attributed to the minor variations in the drag and Reynolds stress profiles within the three canopies. It can also be observed in figure 3b that the expected Kármán constant is not recovered in cases H and H0. This can likely be attributed to not using the correct displacement height, which is generally used while fitting rough wall velocity profiles to the log-law [21]. Rather than fitting the log-law, Mizuno & Jiménez [22] proposed that the linearity of the mixing length scale, 
\[ L_m = u_r (dU/dy)^{-1}, \]

in the channel was a better indicator of the logarithmic region, especially in low Reynolds number flows such as the present cases. Although not shown here, a linear region in the mixing length, \( L_m \), was obtained for all three cases.

An additional feature of the velocity profiles for all cases is the presence of an inflection point near the canopy top. Inflection points have been traditionally indicative of the presence of a Kelvin–Helmholtz-like instability in canopy flows [8, 4, 3]. As discussed in the previous section, the occurrence of such instabilities has been widely reported over dense canopies. Over sparse canopies however, this would depend on the level of sparsity. It is also not clear whether, if formed, these instabilities would be able to maintain their spanwise coherent structure.

### 3.1. Turbulence statistics

Figures 5 (a), (c), (g) and (e) show turbulent fluctuations scaled with the ‘global’ \( u_r \). Outside the canopy, the canopy sublayer, which we take here as the height at which the fluctuations recover to approximately the smooth wall values, extends to about twice the canopy height, which is in the limit observations made by [23, 24, 25] for roughness sublayers of canopies and roughness. Within the canopy, the fluctuations are highly damped for all cases, as compared to the smooth-
Figure 5. Root mean squares of turbulent fluctuations for flow for smooth channel (black), case S (red), case H0 (purple) and case H (blue). Plots in the left (right) column are scaled with $u_\tau (u^*)$. The smooth-wall data is of a channel at $Re_\tau = 550$. 
wall. However, as discussed previously, $u_\tau$ may not be the appropriate scale for comparing the fluctuations. Figures 5 (b), (d), (f) and (h) show the fluctuations rescaled with $u^\ast(y)$ against the local height in wall units, defined as $y^+_w = yu^\ast/\nu$. Note that $u^\ast$ is the same as $u_\tau$ above the height of the canopies, where no drag force being applied. In this local scaling we observe that the streamwise velocity fluctuations for cases S and H0 are similar to those for the smooth-wall. The fluctuations for case S are larger near the head of the canopy, which may be a result of the flow separation around it. However, even though the magnitude of drag force applied in the three cases are within 5 percent of each other, the fluctuations for case H are significantly damped. This can be attributed to the difference in the way the three cases disrupt the near-wall turbulence cycle. As noted by [26], the near wall peak in the streamwise fluctuations and the streamwise vorticity can be considered as indicators of the near wall streaks and quasi-streamwise vortices respectively. In case H0, there is no drag on the streamwise perturbations, and consequently the streaks formed are consistent with the local shear. Similarly, in case S, the streaks can rest between the canopy elements and do not experience much damping due to drag. For case H however, the drag force damps the perturbations through the entire canopy, which results in weaker streaks as compared to the other two cases. We observe a similar trend in the streamwise vorticity, where the off-wall peaks for cases S and H0 coincide, while the peak for case H is more damped. However, the peak in the streamwise vorticity for cases S and H0 in local scaling exceeds the smooth-wall value. The off-wall peaks of spanwise and wall-normal velocity fluctuations, which are mainly generated by vortices, also exceed the corresponding smooth-wall values. In addition, the location of the peaks is also not concurrent with that of the smooth-wall case. This could be due to the local scale for the shear having a wider support in $y$ for the cross velocity components, and not being set merely by the shear at the particular height. Nevertheless, more profound modifications of the dynamics cannot be ruled out with the present evidence.

As case H0 only has a drag in the streamwise direction, as opposed to case S which applies a drag in all three directions, a comparison between them can be used compare the relative importance of the drag in different directions. A comparison between cases S and H0 reveals that the drag force in the streamwise direction alone is sufficient to modulate the level of fluctuations in all directions, and that the spanwise and wall-normal drag forces do not show a significant effect on the flow. This phenomenon can partly be explained by continuity. In addition, as the drag force applied is proportional to the square of the velocity, and as the streamwise velocity is much larger than the other two components, so is the streamwise drag. The streamwise drag modulates the value of the local shear, and consequently sets the scale of near-wall streaks. The near wall-streaks affect the formation of quasi-streamwise vortices, which in turn modulates the spanwise and wall-normal fluctuations [27].

3.2. Spectral analysis
In this section, we analyse the energetically relevant scales within the flow to gauge whether the turbulence structure in the canopy has been modified by the Kelvin–Helmholtz-like instability. This instability is spanwise coherent, and a clear signature of this instability has been known to be observed even in turbulent conditions [8, 14, 28]. In the spectral energy density, $k_x k_y E_{vv}$, these instabilities cause the appearance of a peak, at fixed streamwise wavelength and elongated in the spanwise direction, which is most notable in the spectral energy density of the wall-normal velocity [14, 19]. The streamwise wavelength of the peaks corresponds to the wavelength of the instability.

In figure 6 we compare the spectral energy densities of all cases with that of a smooth channel at a height of $y^+_w = 105$, which roughly corresponds to the tips of the canopy elements, where we would expect the centres of the Kelvin–Helmholtz-like instabilities to lie. For case S, the canopy wavelength, $\lambda^+_x = \lambda^+_z \approx 200$, and its harmonics are visible at the bottom left of the plots. At
Figure 6. Spectral energy densities, $k_x k_z E_{uu}$ (a,e,i), $k_x k_z E_{vv}$ (b,f,j), $k_x k_z E_{ww}$ (c,g,k), and (d) $k_x k_z E_{uv}$ (d,h,l), scaled in friction units, at $y^*_f \approx 105$. The filled contours correspond to smooth-wall data, and the superimposed lines represent from (a) to (d), case S; (e) to (h), case H0; and (i) to (l) for case H. The contour increments, in wall units, are 0.113, 0.039, 0.059 and 0.040 respectively.

This height, the canopy wavelength does not appear to change the energy distribution, with the contours of energy density of the smooth-wall case coinciding with that of case S, for smaller scales. In figure 6a, the damping of larger scales can be observed. As noted by [26], this may imply the shortening of streaks at this height. The damping of large scales in $k_x k_z E_{uu}$ is also reflected in in the co-spectra of the Reynolds stress shown in figure 6d. In $k_x k_z E_{vv}$, shown in figure 6b, we observe the opposite, i.e. a redistribution of energy to larger scales, with a peak in the spectra at $\lambda^*_x \approx 600$, with a corresponding peak in the $uv$ co-spectra. Although it is not certain, this can be a possible reflection of the Kelvin–Helmholtz-like instability.

For cases H0 and H, the turbulent fluctuations appear to have an ‘origin’ which is different to that of the smooth-wall case, and therefore, the smaller scales in the spectra do not coincide with those of the smooth-wall. Even so, some qualitative comparisons between the cases can still be made. The core region of $k_x k_z E_{vv}$ and $k_x k_z E_{ww}$ in case H is smaller than that for the other cases. The reason for this stems from nature of the drag term for this case. As the drag is
proportional the square of the total velocity, the core region of the spectra, which has the highest velocity, experiences the highest damping for case H. As discussed previously, the wall-normal and spanwise fluctuations for the other cases are not much affected by the drag force.

Interestingly, a clear peak in the spectrum of the wall normal velocity, which would be indicative of the Kelvin–Helmholtz-like instability, is not observed in cases H and H0. However, this does not imply that no instabilities have formed in these case. The more probable reason for this is that the instabilities in cases H and H0 are weaker than in case S, owing to weaker inflection in their mean velocity profiles.

Figure 7 shows the spectral energy densities of all cases within the canopy at an effective height $y^+_l = 15$. The height is chosen as it approximately corresponds to the near wall peaks in the averaged turbulent fluctuations. Focusing only on the spectra of $u^2$ and co-spectra of $uv$, we observe for case S, that the fluctuations in the vicinity of the canopy wavelength are distorted. It is also worth noting that, owing to scaling with the local friction velocity, $u^*$, the canopy wavelength has now decreased to $\lambda^+_z = \lambda^+_x \approx 115$. Similar to the effect seen at the canopy tips, cases S and H exhibit shortening of the spectrum of $k_x k_z E_{uu}$, as opposed to case H0 where the larger scales do not appear to be affected. Although, they do not exactly collapse,
the spectrum of the streamwise velocity for all cases appears somewhat similar to that of the smooth-wall. However, in agreement with the observations in the r.m.s velocity fluctuations of $u$ and $v$, the spectra of these velocities are also more intense compared to smooth-wall values at this height. Again, these changes may be attributed to the fact that the local friction velocity is not the appropriate scale for these fluctuations, or, due to the forcing intrinsically changing the near-wall turbulence.

4. Conclusions
The results obtained from preliminary DNSs of flow over canopies with height $h^+ \approx 100$ are presented. Three cases are simulated, the first where the geometry of the canopies is resolved (case S), the second with the canopies modelled as a homogeneous drag force (case H), and the third with the drag force only applied on the mean streamwise flow (case H0). The magnitude and distribution of the average canopy drag force for all cases was maintained to be similar. We found that the streamwise drag had the most impact on the flow within the canopy, and large structures in $u$ were damped for all cases run. In case S, we also observe a redistribution of energy to larger scales, manifested in the formation of peaks at $\lambda_x \approx 600$ in $k_x k_z E_{uv}$ and $k_x k_z E_{uu}$, probably as result of a Kelvin–Helmholtz-like instability. The RMSs of streamwise velocity and Reynolds stress in the sparse canopy were found to be similar to a smooth-wall, when scaled with the local friction velocity at each height within the canopy. However, this local scaling was observed to break down for the wall-normal and spanwise fluctuations. The averaged turbulent fluctuations were found to be similar for cases S and H0, implying that applying a drag on the mean flow alone, and not on the fluctuations, is a better representation of a sparse canopy than applying a homogeneous drag. The drag in case H was observed to have a much larger effect on the streamwise perturbations and, by extension on the near-wall turbulence cycle [27], due to excessive damping of the turbulent fluctuations.

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