Turbulent Structures in Canopy Flows

Antonio Segalini, Jens H.M. Fransson, and P. Henrik Alfredsson

Abstract. A wind-tunnel experiment has been performed by means of a new forest canopy model. Hot-wire anemometry and Particle Image Velocimetry have been used to describe the flow from the statistical point of view together with a conditional sampling approach based on the Variable Interval Time Average method. The analysis demonstrated qualitative agreement between both measurement techniques, regardless of the canopy density that affects the structure intensity but not its topology.

1 Introduction

There is a renewed interest in the description of the atmospheric boundary layer over forested areas due to the strong exploitation of wind energy in Europe but also elsewhere. From the power production point of view, wind-turbine parks located on flat lands or offshore are more ideal as compared to locations in forested areas, but the number of such exploitable sites is limited. Therefore great efforts are spent to characterize the effect of the presence of a forest canopy in order to assess wind-turbine performance and the overall quality of a given site.

Wind-speed statistics profiles have been characterized by many experiments in both wind-tunnel [5, 6] and atmospheric boundary layers [2], providing useful fits of the mean velocity profile. However, there are still debates about the turbulent structures generated by the canopy-atmosphere interactions [8]. Poggi *et al.* [6] suggested that canopy flows show three main types of structures, namely the ones due to the vortex shedding inside the canopy, the ones due to the Kelvin-Helmholtz instability of the velocity profile (which has an inflectional point slightly above the canopy top) and finally the coherent structures typically found in wall-bounded turbulence.

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The distinction between these contributions is not an easy task even in laboratory settings, while it becomes impossible in atmospheric flows due to the limited spatial characterization of the flow field and the continuous changes of the geostrophic wind, which limits the identification of causes-effects of the atmospheric turbulence.

A wind-tunnel experiment has been therefore performed by means of a new forest canopy model. *Hot-wire anemometry* (HW) and *Particle Image Velocimetry* (PIV) have been used to describe the flow from the classical statistical point of view together with conditional sampling methods based on empirical techniques, often used in atmospheric flows [7]. Amongst the various existing methods, the VITA method (*Variable-Interval Time Average*) is here used to study localized variations in the velocity time series obtained from both HW and PIV over the wind tunnel forest model at some detection points [3, 7]. The use of two measurement techniques is expected to shed some light regarding the dynamics of the turbulent structures, since they are complementary techniques.

2 Experimental Setup

The experiments were performed in the Minimum Turbulence Level (MTL) wind tunnel at the Royal Institute of Technology (KTH) in Stockholm. The atmospheric boundary layer is simulated by means of triangular spires at the beginning of the test section to artificially increase the boundary-layer thickness up to 0.5 m. In order to simulate a forest canopy four pin fin plates with a width of 1.2 m and a total streamwise length of 2.0 m have been used. The canopy trees have been replicated by 5 mm diameter wooden circular pins that have been mounted in holes drilled in the plates, where the tip of the pins reaches $h_c = 50$ mm above the plate with a total model length of $40h_c$. The pins can be removed or added in order to create canopies with different densities. All the reported statistics have been measured at the streamwise station $x/h_c \approx 30$. As a notation, y will indicate a vertical coordinate with origin at the canopy top.

Hot-wire anemometry was used during the first part of the experimental campaign to determine statistical properties of the flow. Two HW sensors were used to educe the characteristics of the turbulent structures: A single HW probe (detector probe) and a crossed HW were used to measure time series that subsequently were phase averaged by using the detector probe. Time series have been acquired for five different free-stream velocities ($U_\infty \approx 5$, 10, 15, 20 and 25 m/s) at 20 points across the boundary layers with a sampling frequency of 20 kHz and a sampling time of 120 s in order to achieve good statistics and enough structures for the ensemble average to converge. Since the main statistics profiles did not show any Reynolds number dependence above the canopy (as shown in figure 1), only the phase averaged flow field with $U_\infty \approx 10$ m/s will be shown. During the two-point measurements, the used tree density of the canopy model was 850 pins/m^2, corresponding to an Element Area Index (EAI, defined as the frontal area per unit volume) of 17 m^{-1}.

For the PIV measurements one high-speed C-MOS camera (Fastcam APX RS, 3000 fps at full resolution, 1024×1024 pixels, Photron) was positioned in backward-forward scattering mode at an angle of approximately 90° to the acquisition plane. The raw images from the measurements had a resolution of 1024×1024 pixels and a 10-bit dynamic range. The images were taken at a sampling frequency of 800 Hz. A vertical laser light sheet of 1 mm thickness (aligned with the streamwise direction) was produced by a Nd-YLF laser (Pegasus PIV-Laser). Measurements were made at $U_\infty \approx 5$ m/s and $U_\infty \approx 10$ m/s.The canopy density during the PIV measurements was twice as high (1700 pins/m^2 with EAI= 34m^{-1}), with respect to the one used during the HW measurements, with the aim to quantify the canopy density effect on the educed structure. It is worth to mention that highest canopy density has been previously characterized with HW anemometry and no significant differences were observed in the mean velocity profile and in the Reynolds stress tensor above the canopy, with the exception of the vertical velocity variance, that increases with the increase of EAI.

3 Results

The mean velocity profile and velocity variances and co-variance in the vertical plane are shown in figure 1 for both HW and PIV for all the available U_∞. The friction velocity, u_*, is here used to normalize the velocity statistics and it has been determined from the maximum of the shear stress $-\langle u'v' \rangle$ measured during the HW measurement campaign. The mean velocity profiles from both measurement techniques show quantitative agreement, while the streamwise and wall-normal variances are in reasonable agreement. There are some discrepancies close to the forest probably due to excessive laser light reflection from the ground, or to the limitation of HW anemometry to measure recirculating flows, likely to occur at the canopy top. The statistics for both HW and PIV show that above the forest a high velocity shear is present, together with high turbulence intensity up to approximately $2h_c$. Above $2h_c$ the turbulence starts to decrease with height more rapidly than in the atmosphere due to the lack of free-stream turbulence in the present setup (besides the one provided by the spires), but it clearly points out that at $y \approx 2h_c$ there is the edge of the internal boundary layer due to the presence of the canopy.

The application of the VITA technique [7] to the HW data set allows the detection of time instants where significant variations are observed in the time series of the detection probe. Once these instants have been identified, a phase average can be performed and the associated characteristic structure identified. However, the structure signature will be defined in time, since only single-point time series are available with HW anemometry. Therefore the so called Taylor hypothesis must be applied as $\Delta x(y) = -U(y)\Delta t$, leading to the structure reported in figure 2, which is the phase average of the fluctuating velocity associated to the detection times. The picture of the educed structure is in agreement with atmospheric measurements over forests [1, 7], where large scale structures, educed with such empirical methods, are usually associated to some ejection of low momentum fluid from within the canopy, followed by a strong sweep of high momentum fluid from aloft.

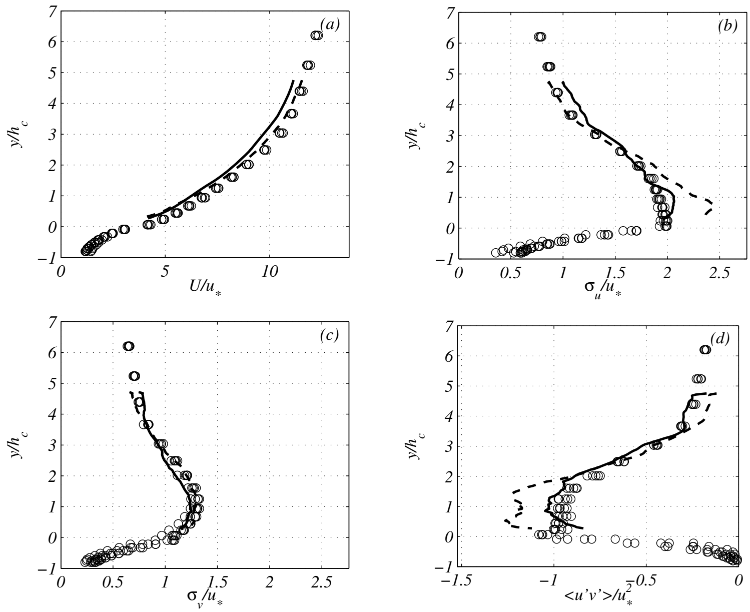

Fig. 1 Comparison of measured statistics profiles with HW with $5\mathrm{m/s} \leq U_\infty \leq 27\mathrm{m/s}$ (Circles), PIV with $U_\infty \approx 5\mathrm{m/s}$ (Solid lines) and PIV with $U_\infty \approx 10\mathrm{m/s}$ (Dashed lines). Mean streamwise velocity (a), standard deviation of the streamwise (b) and wall-normal (c) velocity and Reynolds shear stress (d).

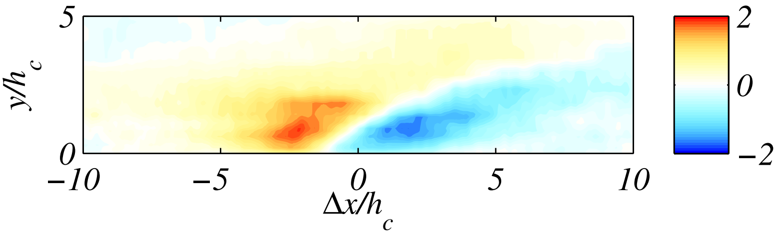

Fig. 2 Conditionally averaged streamwise velocity fluctuation field, $\Delta u/u_*$, detected by means of the VITA technique at $U_\infty \approx 10$ m/s (HW data). The used averaging time is $T_{av} = 0.7h_c/u_*$ with a threshold $k = 1$ [7].

The PIV measurements do not need the use of the Taylor hypothesis and can directly provide a spatial description of the structure. Figure 3 reports the PIV phase averaged structure at different instants relatively to the detection times, providing a slightly different description than the one reported in figure 2. It is possible however to observe that the same ejection-sweep cycle previously described is present but with a stronger structure intensity (probably associated to the different canopy densities).

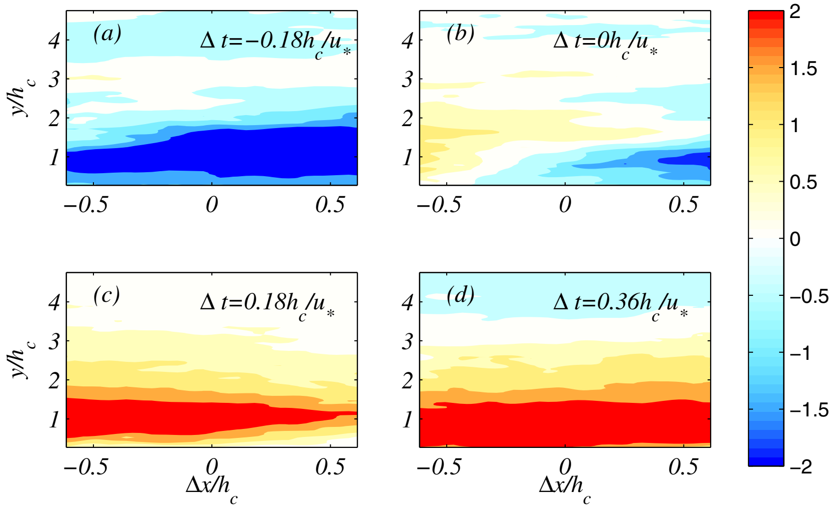

Fig. 3 Time evolution of the VITA structure detected by means of PIV at $U_\infty \approx 10$ m/s. (a)-(d) are subsequent phase averaged velocity fluctuation fields, $\Delta u/u_*$, with $\Delta t u_*/h_c = 0.18$. The used averaging time is $T_{av} = 0.7 h_c/u_*$ with a threshold $k = 1$ [7].

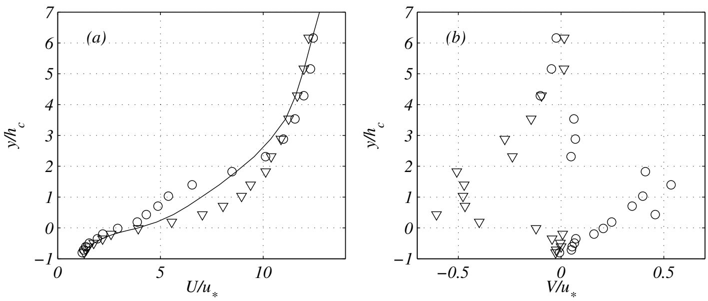

Fig. 4 Effect of the passage of the VITA event on the stream-wise and vertical velocity at $U_\infty \approx 10$ m/s (HW data). (▽) Sweep event, (○) Ejection event.

The effects of the structure passage on the mean velocity profile are more intense close to the canopy, where the highest velocity variation is observed, but they can also be observed even at $y/h_c \approx 5$ in weaker form, according to ref. [7]. Figure 4 shows the effects of such structure on the streamwise and vertical velocity profile. The ejection-sweep cycle is evident and it gives significant variations to the instantaneous wind velocity in a short amount of time, a phenomenon that might increase fatigue loads, as discussed by Odemark [4].

4 Conclusions

The effect of a forest canopy on the atmospheric boundary layer has been analyzed in the present work by means of simple statistical tools and phase averaged maps. Velocity statistics have been provided from both hot-wire anemometry and PIV, showing a good agreement in the mean velocity profile and a reasonable agreement in the covariances.

The VITA technique has been subsequently used to determine the instants where footprints of large scale passing structures were present, identified by means of a sudden variation in the velocity signal. The use of two independent measurement techniques allowed the comparison of the same eduction method by using measurement techniques with different time and space resolutions, together with an assessment of the outcomes of such empirical techniques, often applied to single-point statistics. Despite the fact that the VITA eduction method is not based on any velocity spatial gradient information, used in more sophisticated eduction criteria, its outcomes are noteworthy because they are associated to sudden streamwise velocity variations, events that have important implications in both wind-turbine energy production and fatigue loads.

The comparison of the structures educed with both techniques showed a qualitative agreement, demonstrating that the educed event is composed by an ejection-sweep cycle and it is convected downstream with approximately zero vertical velocity. However its intensity seems to increase with the increase of the canopy density, a property that clearly underlines the link between the educed structure and the canopy boundary condition. The effects of the passage of the educed structure on the mean wind speed profile have been demonstrated, pointing out that such large scale structures can enhance fatigue loads and provide challenges to pitch control systems of modern wind turbines located over forests.

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References

1. Bergström, H., Högström, U.: Turbulent exchange above a pine forest. II. Organized structures. Bound-Lay Meteorol 49, 231–263 (1989)
2. Högström, U., Bergström, H., Smedman, A.-S., Halldin, S., Lindroth, A.: Turbulent exchange above a pine forest, I: Fluxes and gradients. Bound-Lay Meteorol 49, 197–217 (1989)
3. Johansson, A.V., Alfredsson, P.H.: On the structure of turbulent channel flow. J. Fluid Mech. 122, 295–314 (1982)
4. Odemark, Y.: Wakes behind wind turbines - Studies on tip vortex evolution and stability. TRITA-MEK technical report 2012:06, Stockholm (2012)
5. Raupach, M.R., Finnigan, J.J., Brunet, Y.: Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy. Bound-Lay Meteorol 78, 351–382 (1996)

6. Poggi, D., Porporato, A., Ridolfi, L., Albertson, J.D., Katul, G.G.: The effect of vegetation density on canopy sub-layer turbulence. Bound-Lay Meteorol 111, 565–587 (2004)
7. Segalini, A., Alfredsson, P.H.: Techniques for the Eduction of Coherent Structures from Flow Measurements in the Atmospheric Boundary Layer. Bound-Lay Meteorol (2012), doi:10.1007/s10546-012-9708-7
8. Shaw, R.H., Schumann, U.: Large-eddy simulation of turbulent flow above and within a forest. Bound-Lay Meteorol 61, 47–64 (1992)