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A study on the inclusion of forest canopy morphology data in numerical simulations for the purpose of wind resource assessment

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ABSTRACT

A series of numerical simulations of the flow over a forest stand have been conducted using two different turbulence closure models along with various levels of canopy morphology data. Simulations have been validated against Stereoscopic Particle Image Velocimetry measurements from a wind tunnel study using one hundred architectural model trees, the porosities of which have been assessed using a photographic technique.

It has been found that an accurate assessment of the porosity of the canopy, and specifically the variability with height, improves simulation quality regardless of the turbulence closure model used or the level of canopy geometry included. The observed flow field and recovery of the wake is in line with characteristic canopy flows published in the literature and it was found that the shear stress transport turbulence model was best able to capture this detail numerically.

1. Introduction

The numerical theory describing flow through forest canopies has been developed over a number of years. This process has been driven by a need for robust wind resource assessment and also for agricultural applications such as modelling wind loads on isolated forest stands and optimisation of the spraying of pesticides.

A wide variety of computational fluid dynamics (CFD) approaches have been employed with, for example, Yang et al. (2006) favouring the use of large eddy simulation (LES) in order to fully appreciate the turbulent structures which develop across forest edges. LES simulations were also used by Dupont et al. (2010) to investigate the importance of transient effects such as the waving of leaves and branches.

However, for most practical applications, it has been suggested that simpler two equation turbulence models suffice when considering canopy flows (Belcher et al., 2012). This is due to the fact that, although highly turbulent, the flows in these regions are not dominated by the effects of viscosity. This matter will be given further consideration in Section 2.6.

There has been considerable activity investigating how best to implement the effect of canopies in two equation turbulence models and a state of the art has emerged following contributions by Svensson and Haggkvist (1990), Liu et al. (1998), Sanz (2003) and Lopes da Costa (2007). More recently, these two equation canopy models have been modified to include buoyancy effects due to atmosphere stability (Sogachev et al., 2012) and so it is likely that they will continue to be of use to industry for some time to come.

In addition, the ability to assess the structure of canopies has also progressed. From the collecting and counting of leaves to the use of various photographic and high density Light Detection And Ranging (LiDAR) techniques, a review of these developments can be found in Jonckheere et al. (2004) and Seidel et al. (2012). In Omasa et al. (2006), a high level of canopy structural detail was acquired using a method which combined GPS, airborne and terrestrial LiDAR as shown in Fig. 1. These data were then combined with temperature and chlorophyll fluorescence measurements in order to allow detailed modelling of the plant physiology.

Various authors have suggested that these parallel advances in numerical theory and the ability to capture morphology data could be used in combination to reduce the uncertainty associated with modelling canopy flows.

In Endalew et al. (2009a), it was noted that much work has been carried out in accurately capturing the structural detail of

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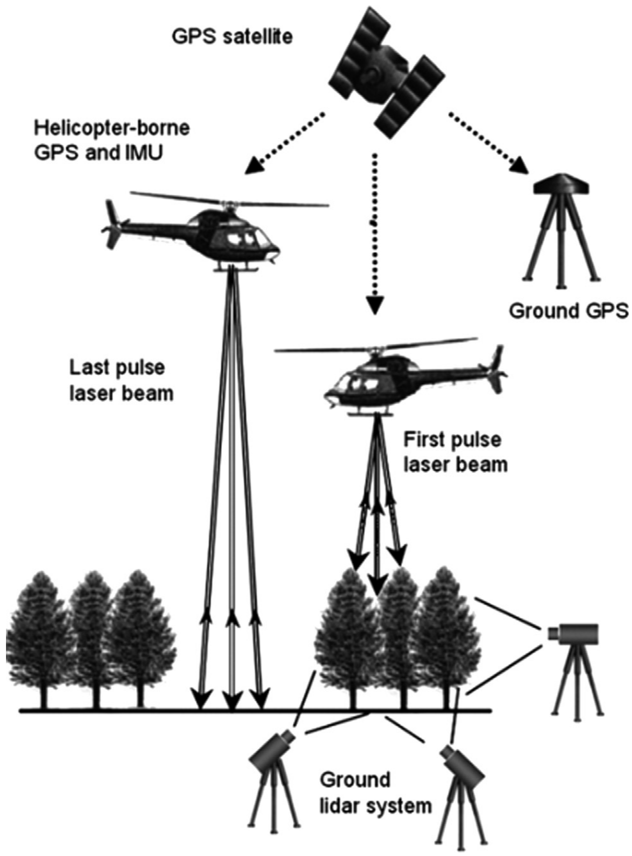

Fig. 1. Capturing canopy structural data. From Omasa et al. (2006).

forest canopies, but little effort had been expended to implement this in CFD modelling. These authors used an extremely high level of canopy detail to conduct CFD modelling of flow around a pair of model trees using LES. Individual branches were explicitly modelled and the effect of the leaves was introduced within tight fitting porous sub-domains around each branch. Simulations were validated using wind tunnel data and it was found that this high level of canopy detail improved the quality of the CFD results albeit at a considerable computational expense.

More recently, Burns et al. (2011) pointed to the importance of canopy morphology based on investigations of data from five forested sites and suggested that the required structural data would be best captured using high density LiDAR systems. In Dupont et al. (2012), a number of LES simulations were conducted based on forested site data and in Lee and Lee (2012), the flow around a bank of real fir trees was investigated by use of Stereoscopic Particle Image Velocimetry (stereo-PIV) in a wind tunnel. Again, both Dupont et al. (2012) and Lee and Lee (2012) concluded that an understanding of the actual morphology is vital when modelling canopy flows.

Whilst a body of opinion clearly exists that CFD simulations will benefit from the incorporation of morphology data, it is important to note that the work mentioned above is concerned with aspects of canopy flow such as wind loading on individual trees and turbulent structures within canopies. Whilst of interest, these factors may not be directly applicable to the concerns of the wind energy industry. In this paper, we will focus on elements of the flow above and around canopies of direct relevance to the resource assessment community. These are the modulus of the mean wind speed, $|\overline{U}|$, and mean turbulent kinetic energy (k).

In order to provide an extensive validation database, experiments have been conducted in an atmospheric boundary layer wind tunnel to investigate the wake around a stand of 100

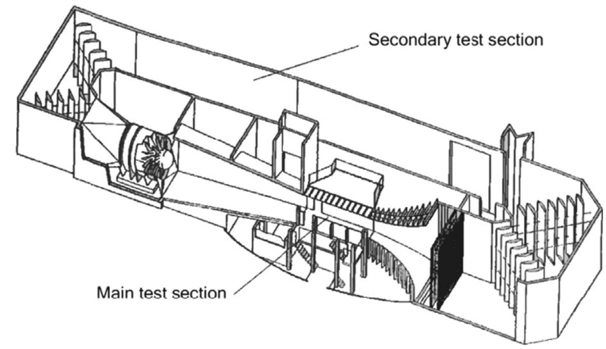

Fig. 2. Schematic view of the wind tunnel in University of Orléans.

architectural model trees. Subsequently, canopy morphology data were captured using photographic analysis software and a series of CFD simulations were conducted in which increasing levels of detail were gradually introduced. By analysing the quality of these simulations, we have investigated whether a detailed understanding of the canopy structure is beneficial when modelling flow around a forest canopy for the purpose of wind resource assessment.

2. Experimental data

2.1. Tunnel description

Experiments were conducted in the Lucien Malavard wind tunnel which is located in the Laboratoire Prisme, University of Orléans, France. As can be seen from Fig. 2, this is a close-return wind tunnel in which two sections are available for testing. Experiments for this study were conducted in the 5 m wide × 5 m high × 12 m long secondary test section which utilises a turbulence grid, turbulence spires and a rough metallic floor plate to generate a scaled atmospheric boundary layer to a maximum wind speed of 10 m/s.

Measurements were performed using stereo-PIV (Schröder and Willert, 2008). The flow was seeded with a fine mist of olive oil (1 μm in diameter). The area of interest was illuminated by use of an Nd-YAG twin laser (model CFR PIV 190, manufactured by Big Sky Laser, 200 mJ/pulse) to generate a laser light sheet. In order to acquire the required images, two POWERVIEW Plus 4M cameras (model 630059, 2048 × 2048 pixel resolution) were positioned to capture a stereoscopic view of the illuminated flow field. Both cameras and lasers were synchronised by use of a LASERPULSE module (model 610035) with a sampling frequency of 7 Hz, the maximum allowable by the equipment. Signal acquisition and processing of raw data were then performed using Insight software, provided by TSI, to produce a three dimensional flow field for the plane under investigation.

The setting of the stereo-PIV was performed by using the TSI Dual Plane/Dual Sided calibration target. A total of 2000 images were captured for each of a series of concatenated 360 mm wide × 350 mm high measurement planes. An overlap of 60 mm was used between planes in order to improve the merging of data through linear interpolation.

An adaptive interrogation window was used, starting from 64 × 64 pixels to a final 32 × 32 pixels window. The interrogation window overlap was 25% and the analysis was based on FFT Correlation algorithm and the Gaussian peak fitting technique. Analysis of these data allowed both mean and variances to be deduced for the three main instantaneous wind speed components U, V, W.