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A robust videogrametric method for the velocimetry of wind-induced motion in trees

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ABSTRACT

Wind has major effect on plants, from growth changes to windbreaks. Therefore, there is a crucial need for non-invasive methods to describe and quantify the complex motion of a plant induced by wind. In this paper two methods based on video sequences analysis are studied. An adaptation of the classical Particle Image Velocimetry method (nat-PIV) is compared with a tracking method based on the optical flow method of Lukas and Kanade, initialized with the features selection method of Shi and Tomasi (ST + KLT). Both methods were benchmarked on an experiment on a walnut tree in open-field conditions submitted to different wind flows at different periods of the year and equipped with 3D magnetic tracking. The metrological assessment was performed in two steps. We first tested if the results given by both methods were significantly different. Secondly, a direct assessment of the two methods versus 3D magnetic tracking was performed. The ST + KLT method proved to be more accurate and robust than nat-PIV one. The outputs of the ST + KLT method are independent of the foliage density, wind velocity and of light gradient intrinsic to outdoor scene. The implementation of ST + KLT method developed for this study in Matlab is freely available.

1. Introduction

Wind hazards on plants are a major problem in agriculture and forestry because of the yield losses they entail (Berry et al., 2003; de Langre, 2008; Gardiner, 2000). For example annual yield losses due to lodging in cereals amounts 20% world wide despite the selection of short-sized genotypes. In forestry, recurrent storms damages have emphasized the need for forest management limiting damage to trees (Achim et al., 2005). This has fostered a long-term interest on the biomechanics of wind–plant interaction (see rev in Moulia and Fournier, 1997; Gardiner et al., 2008; de Langre, 2006). For windbreaks, it has been shown that the dynamic component of wind loading and the inertial loads due to wind induced accelerations must be considered (Gardiner, 2000). Moreover, branches may reach their breaking limits before the basis of the trunk, acting as security fuses (Hedden et al., 1995; Niklas and Spatz, 2000; Lopez et al., 2011). Wind is also influencing plant growth, through gas exchanges (de Langre, 2006).

Finally the deformations induced by chronic winds are sensed by the plant, giving rise to an acclimation and hardening growth process called thigmomorphogenesis (reviewed in Moulia et al., 2011). This includes dramatic change in growth in height and girth, as well as the production of special woods such as flexure wood and eventually, when non-elastic bending/tilting, occurs, reaction wood (Telewski, 2006).

The motion and deformation of plants under the wind can be complex, and depends both on the architecture of the plant (Sellier et al., 2006; Rodriguez et al., 2008) and on its environment (e.g. isolated tree vs trees in a forest canopy, de Langre, 2008) For example the wind–canopy interaction is initiated by the Kelvin–Helmoltz instability (Raupach et al., 1996) shedding a cascade of vortex waves called Honamis (Py et al., 2005; Dupont et al., 2010). Additionally the response of the plant itself may be complex. Indeed many

Abbreviations: nat-PIV, Particle Image Velocimetry method over natural texture; ST + KLT, Lukas Kanade method coupled with Shi and Thomasi features selection; *ts*, abbreviation used to describe a condition of the test set $ts \in \{DHighW, DMediumW, IHighW, IInterW\}$; Meth, suffix corresponding to the method used to compute the velocimetry field. $Meth \in \{OPt, Magnetic\}$ and $Opt \in \{ST + KLT, nat\text{-}PIV\}$.

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Nomenclature

Velocimetry notations

$V_{ts,Meth} = V_{ts,Meth}(x,y,t)$ velocimetry vector field obtains for all the sequences corresponding to the test set ts with the method *Meth*. The coordinates *x*,*y* corresponding to the geometrical center of grid unit; *t* is the time

$\langle V_{ts,Meth} \rangle$ spatial and temporal average of the velocimetry obtained by the method *Meth* for the test set *ts*

$\overline{V_{ts,Meth}}$ temporal mean of the velocimetry calculated to compare nat-PIV and ST + KLT measurements with magnetic ones

τ_c, τ_{rs} time periods of the camera (0.04 s) and commun time period to magnetic and numeric measurements (0.2 s)

Statistical treatments

a_{ts} slope of the orthogonal regression lines

$a_{ts,sup}$ $a_{ts,inf}$ the confidence interval of the slope

b_{ts} intercept of the orthogonal regression lines

R_{ts} correlation coefficient

modes of wind-induced vibrations can be characterized (Sellier et al., 2006; Rodriguez et al., 2008).

Different models for the various wind-induced effects have been developed (e.g. Sellier and Fourcaud, 2005; Py et al., 2006; Gardiner et al., 2008; Rodriguez et al., 2008; Dupont and Brunet, 2007; Moulia et al., 2011), some of them including the motion and deformation of all the branches (e.g. Sellier and Fourcaud, 2005; Rodriguez et al., 2008) or of a continuous canopy (Py et al., 2006; Dupont et al., 2010). However to date measurements of wind-induced motions were not obtained with such a detail. In most case, only local displacement were measured by mean of inclinometers, strain gauges and laser-beam (Flesch and Grant, 1992a, 1992b; Hassinen et al., 1998; Sterling et al., 2003; Sellier et al., 2006) or, more recently, through a set of magnetic 3D trackers (Rudnicki and Burns, 2006; de Langre et al., 2012). Local measurements do not allow for a characterization of many features of wind induced motion in plants. Honamis or vibration modes can hardly be characterized (Py et al., 2005) nor the signal triggering the plant thigmomorphogenesis, that involves a spatial integration of the strain field over the whole plant (Moulia et al., 2011). Moreover some plant organs (e.g. small branches, leaves) may be light-weighted and the mass or the geometry of some sensors may alter the dynamics of the plant.

There is thus a crucial need for a more extensive description of wind induced motion by a non-invasive velocimetric characterization, i.e. the quantification of the spatio-temporal vector field of the velocity of motion of the different plant parts. Velocimetric non-invasive measurements using video images videogrametric analyses are standard in fluid and solid mechanics with the widespread use of Particle Image Velocimetry (PIV, Raffel et al., 2002). Concurrently, another type of methods based on optic flow has been developed independently in the area of computer vision (Baker and Matthews, 2004). Although related, the principles and software implementation of these methods differ. The image-processing algorithm of the PIV belongs to the block-matching methods since it is based on the computation of the cross-correlation between image patches in sequential images. In it standard use in fluid mechanics, it usually requires the seeding of the moving flow with artificial markers and specialized and controlled laser lighting, so that the texture of the images meets the assumptions of the PIV algorithm. Optical flow methods are based on the assumption that changes in the gray-level intensities of sets of pixels between successive images results from the (unknown) motion of the material particles in the scene relative to the camera.

PIV has been mostly used for the measurement of fluid flows. Optic flow methods (Horn and Schunck, 1981) have being applied to many complex scenes including moving people, crafts or animals. In particular a robust algorithm proposed by Lukas and Kanade (LK) (Lucas and Kanade, 1981) has been used widely and has been improved by the definition of a pretreatment to LK detecting the “good features to track” in the sequence for a more accurate velocimetry (Shi and Tomasi, 1994, this methods will be noted ST + KLT in the following). In ST + KLT the “good features to track” are defined as displaying orthogonal gray-level gradients, so that their tracking can be optimal in every direction.

These methods are known to have different advantages and drawbacks. The PIV method outputs dense velocity fields. But it may be sensitive to the texture of the image and displays possible peak locking, a systematic tendency to bias toward integer values of motion when the pixelisation of the image is too coarse relative to the amplitude of the motion. Multipass algorithms are used to improve resolution and to decrease peak-locking but require extensive computation time. The KLT method is computationally much faster thanks to the linearization of the equation determining the velocity between two consecutive frames. However, this linearization may introduce critical instability at locations where the images shows poor texture. Moreover it is prone to the aperture problem which is an optical illusion making the local determination of the movement impossible. These two limitations can be solved using a features selection such as in Shi and Tomasi (1994). However, this features – selection step makes the ST + KLT outputs sparse. Finally both methods, PIV and ST + KLT, assume small displacements between successive images, although a standard multi-resolution implementation of KLT allows larger displacement to be handled (Bouguet, 2000; Bradski, 2000).

A modified PIV method using foliage as natural texturing markers (noted nat-PIV thereafter) has been instrumental in characterizing honami-induced velocity field of plant tips in dense canopies of alfalfa and wheat crops (Py et al., 2005). And this unique data set has been used to assess several wind–canopy interaction models (Py et al., 2005; Dupont and Brunet, 2007; Dupont et al., 2010). However, the study of homogeneous dense crops is likely to be the simplest case to be studied, as the top of a dense plant canopy is often planar and displays mostly 2D motion. In most cases though, the structure of the scene of interest may be much more complex. Canopy can be sparse, and isolated plants with complex structure such as trees need to be considered (Sellier et al., 2006; Rudnicki et al., 2001). Additionally, the amount and colors of foliage elements can vary widely over the seasons.

A proof-of-concept test for the use of the ST + KLT method to analyze has been conducted on a few complex isolated plants such as bonsai tree (Diener et al., 2006).

However none of these two methods have been submitted to metrological assessment for the wind-induced motion of complex plants structures in different conditions of wind, foliage and background. Moreover the criteria of choice for one method vs another are unclear. Is there one robust and versatile method for velocimetric measurements of plant motion, or are the two types of methods complementary? Is there a method that is more accurate? Does this depend on wind intensity or on the amount of foliage? Do variations in the amount of lighting over space and time or the background (sky, soil) alter the measurement?

The aim of the paper was thus to assess and compare the two methods versus reference magnetic tracking measurement in a combination of wind, foliage, lighting and background. This “benchmarking” was conducted in the most challenging configuration; namely a complex tree in the field, with natural lighting and changing sky background, in a sample of different weathers and seasonal