Numerical analysis of the influence of the aerial structure on tree dynamics

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Introduction

Wind is the primary physical agent of damage to harvested forests. The evaluation of tree stability to wind involves numerous, potentially coupled factors which are related to both the plant structure and its surrounding media. Over the past decades, the problem has been widely investigated by usually focusing on a particular component of the system such as the soil/root interface (Coutts 1986), the wind action (Oliver and Mayhead 1974) or the stem mechanics (Gardiner et al. 2000). The known, active turbulence of the air flow within forest canopies (Finnigan 2000) has led to model trees submitted to wind loads as dynamic structures since an early stage (Papesch 1974). Branches and especially their oscillations have been acknowledged to have a strong impact on dynamics of the whole aerial system (Scannell 1984, Sellier and Fourcaud 2005). As a consequence, recent models of a tree submitted to a dynamic load include branches as vibrating axes coupled to the stem (Fournier et al. 1993, Saunderson 1997, Moore 2005). This study presents a series of numerical experiments designed to investigate the tree mechanical response to a turbulent air flow as a function of the aerial system, its morphology and materials.

Material and Methods

Reference tree material

The study is done on a tree for which structural characteristics varied around a state of reference. Aerial morphology is provided by a numerical model of a 35-year old Maritime pine (*Pinus pinaster* Ait.) that was simulated with the AMAPsim software (AMAP CIRAD, Barczi *et al.* 2007). Growth parameters used in AMAPsim have been measured by Coudurier *et al.* (1993) in a Maritime pine stand site near Bordeaux, France (see also Heuret et al. 2006). As partially resulting from stochastic processes, the simulated tree corresponds to a possible and realistic one yet not to the mean tree of the stand. In an attempt to maintain practical computational time with the Finite Element analyses (cf. 2.5), all axes with a branching order greater than 3 have been removed from the topological structure. Properties used as reference for wood and foliage materials originate in the literature relevant to the studied species.

Test factors

Characteristics of the structure that have been included in the analysis fall into two different sets, each one independently tested. The first set relates to the geometry of the aerial system, including length and diameter of axes as well as the angle locally formed by the primary branches with the stem. The second set of factors encompasses physical – i.e. wood density, specific leaf area (SLA), linear leaf density – and mechanical – i.e. wood longitudinal modulus of elasticity and viscosity – characteristics of the structure. All factors vary separately for each branching order except for the insertion angle and SLA. Crown topology remains the same during the analyses. Altogether, influence of 20 independent factors on tree dynamics is assessed.

Experimental designs

Fractional experimental designs have been employed so as to minimize the number of simulations to be performed. For each set of factors, either geometrical or material, a design is done twice. The first run corresponds to the simulation of free sway. The analysis aims at identifying frequency and damping of the first bending mode of vibration. The second run corresponds to forced sway and allows calculating tree displacements and the bending moment as caused by wind loading. Each factor has 3 modalities: the reference state, -20% and +20% of the reference value. In this study, a Taguchi (1987) table is used to obtain 27 combinations of factor modalities instead of a full factorial design which would lead to 3^7 and 3^{11} modal combinations for the geometrical set of factors and the material one, respectively.

Theoretical wind velocity

The time series of streamwise wind velocity are representative of the turbulence that occurs within forest canopies. To a large extent, flow characteristics are generic among plant canopies provided that they are normalized by the mean canopy height and/or mean velocity at canopy height. Wind parameters have been chosen to obtain flow dynamics similar to the ones measured in Maritime pine forests near Bordeaux. The tree is submitted to 3 successive gusts, each with a time pattern as observed by Collineau and Brunet (1993).

Finite Element model

For each factorial combination, the mechanical analysis is performed with a Finite Element model relying on ABAQUS software (ABAQUS Inc., Providence RI, USA). A numerical routine generates a FE mesh from the tree originally described as a Multiscale Tree Graph (Godin and Caraglio 1998). Stem and branches are discretised into beam elements while foliage is aggregated on the branches. The equations of movement are solved iteratively by direct time integration (see Sellier *et al.* 2006) and are in the discrete form:

$$M\ddot{q} + D\dot{q} + Kq = G\,(+F) \qquad (1)$$

where *M*, *D* and *K* are mass, damping and stiffness matrices, respectively. $\ddot{q},\dot{q},q$ are the acceleration, velocity and displacement column vectors, respectively. G and F are the column vectors of gravitational and drag forces. In the case of wind-induced sway, F is applied to the structure and accounts for velocity of elements relatively to the flow:

$$F = \rho C_D A(U - \dot{q})\,|U - \dot{q}| \qquad (2)$$

where ρ is air density, C_D the drag coefficient, A the exposed area and U the streamwise velocity of the flow, which depends on altitude in the canopy.

Results

Free sway

Among tested material factors, the most influential one on the frequency of tree natural sway is the modulus of elasticity (MOE) of the stem. The frequency scales up with MOE as expected in structural dynamics since frequency roughly depends on a stiffness over mass ratio. On the other hand, the MOE of branches has almost no effect of the sway frequency. Wood density has a negative influence which is stronger in the case of 2^{nd} and 3^{rd} order axes. Then, the increase in the density does not only contribute to increase the tree mass but also to displace the position of the mass centre upward, both aspects leading to a decrease in the sway frequency. The main factors having an effect on the damping ratio of the tree are the viscosity of the wood material and the specific area of the foliage, which are respectively related to material and aerodynamic damping. The remaining material factors have a very limited influence on motion damping.

Among geometrical factors, the diameter of the stem has the highest impact on the sway frequency. As the diameter increases, so does the frequency. This results from the stiffness of the axis scaling up with diameter as a 4^{th} order power law whereas the volume hence the mass only depends on the square of diameter. The second most influential factor is the length of the stem. An increasing length has a negative influence on the sway frequency since it induces a linear decrease in the relative stiffness of the stem as well as an increase in the height of the centre of mass. Overall, variations of the damping ratio that are caused by geometrical factors are weak.

Wind loading

MOE of the stem is also found to be the most important factor regarding the maximal bending moment over time at the basis of the stem, BM_{max}. The more flexible the stem is, the more it can bend under wind action and then be submitted to lower wind speeds, i.e. lower drag forces. The same influence is observed for the primary branches although the influence is less pronounced. An increase in wood density of branches also causes BM_{max} to increase as a result of higher inertial effects in the crown. Factors that are effective on the damping of trees oscillation such as wood viscosity and foliage area also contribute to slightly reduce the magnitude of the bending moment as they increase.

All geometrical factors have a significant effect on BM_{max}. Of particular interest, the angle of insertion of the primary branches in the stem causes major variations. When the angle is small with the stem, branch extremities are submitted to high wind speeds and consequently important drag forces. On the contrary, when the angle is large, branches are submitted to relatively lower wind speeds. The influence of this factor is especially strong as the mean horizontal wind speed decays exponentially in plant canopies.

Conclusion

The study shows the predominance of the morphology of the aerial system over the characteristics of its constitutive materials as far as tree stability to wind is concerned. This aspect is likely to be even more pronounced in field conditions where geometrical variability of trees is much higher than what we accounted for. Additionally, results point out that tree oscillations are mainly driven by stem characteristics although crown elements are also found to have remarkable and significant effects on dynamics of the entire structure.

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