Analysis of the relationship between tree structure and biomechanical functions

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Introduction

The relationship between tree structure and biomechanical functions is a key component in explaining the diversity of plant shapes, including both aerial and belowground organs. It is now well known that plants are able to adapt to recurrent, external mechanical stresses, with changes in growth and morphology, which in turn increase stability and resistance to wind loading.

This paper aims to review the recent developments that have been carried out in LRBB (Laboratory of Wood Rheology of Bordeaux, France) (Fourcaud et al., 2003c), in order to investigate tree stability. The role of the tree architecture in both root anchorage and aerial crown oscillation under aerodynamic loadings is shown. The interest of including these biomechanical factors in process based models is discussed with regards to applications in forestry.

Mechanical behaviour of the aerial architecture under dynamical loading

Several recent studies assume that tree growth can be influenced by dynamic rather than static external forces (Telewski, 1995; Berthier, 2001). As tree breakage during strong storms results usually from such dynamic solicitations (Wood, 1995), it can be postulate that tree shape can be partly modified due to a specific adaptation to experienced non static stresses. Answering this fundamental question can only be supported by mechanistic arguments. For this purpose, LRBB recently initiated studies which aim to reveal the role of the aerial architecture on the tree mechanical response to dynamic loads (Sellier et al., 2003).

Figure 1: Example of a scalogram of stem motion. Time is plotted on the x-axis and the swaying period is plotted on the y-axis. The gray levels correspond to the signal amplitude; the darker the shade, the higher the amplitude of sways is at the considered time and swaying period. This scalogram shows 2 oscillation modes. The mode of lowest period disappears after the branch movements were synchronized.

First investigations were performed on 3 Maritime pine saplings that were located in an experimental plot at Pierroton in South-West of France. The aerial parts have been first digitized using 3space FASTRAK and coded under a MTG format (Godin et al., 1998) using DIPLAMI software (Sinoquet et al., 1997). These 3D structures were subsequently computed and analysed in terms of topology and geometry, and will be used for numerical analysis. Free oscillation tests were carried out by initiating structural motions with a rope in two perpendicular directions. Oscillations of both branches and stem were recorded using inclinometers and strain gauges. Experiments were repeated after removing the needles and progressive pruning of the branches in order to put into evidence the relative role of the different vegetative elements on the tree mechanical behaviour. The resulting signals were analysed using complex Morlet wavelets (Figure 1). Inter tree and intra tree comparative studies dealt with both sway frequencies and damping ratio. The damping ratio is the ratio between the damping of the structure and its critical damping, where the critical damping is the amount of damping that avoids oscillations. For instance, a 10% damping ratio means that the amplitude of the oscillations is dived by two at each period.

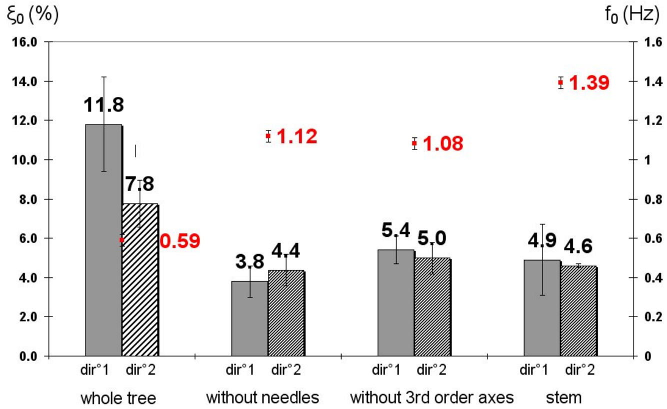

Figure 2: Evolution of dynamic characteristics (damping ratio ξ0, frequency f0) during the pruning performed on the trees (T1) and (T2). Bars represent average damping ratio for both perpendicular test directions.

First results pointed out the major role of needles on the structural motion damping as well as in coupling the motions of the different branching orders (Figure 2). It was also shown that third order axes significantly participate to the dissipation of motion energy while representing 1% only of the total biomass. This last point confirms that the relative positions of crown branches, which are a specificity of plant architecture, must be taken into account to investigate tree sway. Further analyses are in progress in order to study the influence of morphological variables, e.g. crown topology and branches geometry, on tree swaying. For that purpose, numerical techniques, i.e. finite element methods, are used to simulate trees movements on a computer.

Mechanical behaviour of the root anchorage under static loading

Tree root architecture constitutes a complex system as its development can be strongly affected due to the surrounding soil physical properties. It is also well established that root structure can be significantly modified during growth in order to improve anchorage performance of trees (Stokes et al., 1995; Nicoll and Ray, 1996). In order to tackle this last point, it is necessary to understand more the mechanical processes that are involved in the ground when trees are submitted to external forces, e.g., wind or self weight. For this purpose, LRBB initiated studies which aim to enlighten the role of specific root elements as well as soil mechanical properties on tree ability to resist uprooting (Dupuy et al., 2003).

Experimental studies remain largely incomplete in this field of research due to the lack of suitable measurement tools. Most of mechanisms taking place during overturning or plant pull-out is happening underground, which make experimental analysis difficult. Mechanistic modelling provides a powerful alternative which can offer a large overview of the involved processes, enabling to monitor mechanical stresses in roots and soil when tree is submitted to bending forces for instance. For this reason, a generic approach of investigation has been developed. This approach allows real or simulated root architecture to be tested in different soil conditions. The mechanical system, including both soil and roots, is analysed using numerical calculations. These calculations are performed using the finite element method which is a discretization technique to solve equilibrium equations in mechanics (Fourcaud & Lac, 2003).

The first stage consists in coding the topology and geometry of real root systems under a MTG file format. These data are then read by a program that automatically generates a command file which can be used by the ABAQUS finite element software in order to perform mechanical calculations. This command file contains different parts that describe respectively the 3D mesh of the root/soil system, the constitutive laws of the wood and soil materials (Modulus of Elasticity, Modulus of Rupture, etc.), the loads that are applied on the structure, and the calculation options. After proceeding to finite element calculation with ABAQUS, the results can be analysed by the way of the force vs. displacement curves that usually characterise the mechanical behaviour of a structure. The comparative analyses are finally carried out using resulting structure stiffness, i.e. the initial slope of the force/displacement curve, and strength, i.e. the maximum force reached before failure, as criteria (Figure 3).

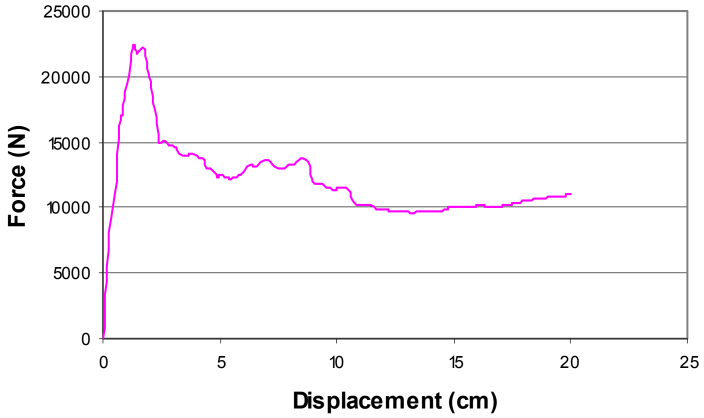

Figure 3: the force/displacement curve, that is determined at the point of the trunk where the horizontal concentrated load has been applied, allows the mechanical behaviour of the structure to be characterised. This curve is a result of the finite element calculation. The initial slope of the curve is defined as the structure stiffness. The first maximum force that is reached before the curve decreases corresponds to the mechanical strength.

This general approach has been used in order to test the influence of soil properties on the anchorage of typical poplar root systems that were measured on the field. The calculations were performed applying a horizontal concentrated load at 7m high on the trunk. It was shown that, for a given root system, the uprooting processes were different between sand and clay soil conditions. Clays were found to be more resistant than sandy soil. However, the most significant effect of soil type was observed on the mechanisms happening during failure.

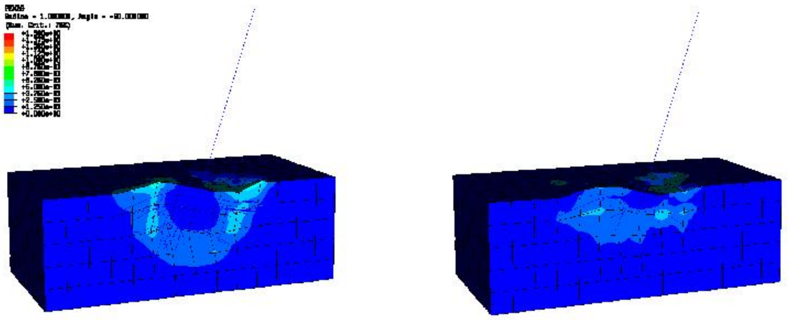

Figure 4: Field of equivalent plastic strain in the soil cross section, which shows the zones that have been irreversibly deformed, for a) herringbone and b) plate root systems in dry sand. The calculations were performed applying a horizontal concentrated load at 7m high on the trunk. Despite the apparent disparities in failure modes, the differences of resistance to bending are rather similar.

Influence of typical root patterns on tree stability has been also investigated. For this purpose, a generator of schematic root structure has been developed. It is based on continuous stochastic processes. Four typical root systems, i.e., taproot, heart, herringbone and plate roots were generated. It was found that the differences in topology and architecture led to large changes in the type of failure and in the overall resistance to bending (Figure 4). The heart root system was found to be the most resistant to overturning on clay soils, but on sandy soils, the deep tap rooted system was better anchored. The herringbone root system was only slightly more resistant than the plate root system, which was always the least resistant to bending. The tap root system was clearly very sensitive to changes in soil conditions, whereas the other systems appeared to be less affected by different soil conditions.

Finally, this approach has been used in order to investigate the mechanical behaviour of real maritime pine root systems that were measured after the 1999's storm in the Aquitaine forest, South-West France (Fourcaud et al., 2003b). Numerical analysis have been performed on these structures without considering soil matrix and applying bending forces in the direction of prevailing wind and perpendicular to this direction. It was shown that the root systems were significantly less resistant in this last direction. This important result confirms the ability of trees to reinforce their stability in accordance with experienced wind.

Including biomechanical concepts in tree growth models

The effect of the branching pattern on the biomechanical behaviour of trees has been discussed above. These investigations have been carried out at a particular stage of the tree development. The tree was then considered as a classical passive structure. Nevertheless, it is necessary to take into account the structural evolution of the plant during its growth in order to investigate the biomechanical response to long term loading.

A biomechanical model has been already developed and implemented in the growth modelling software AMAPpara (CIRAD, Montpellier, France) (Fourcaud and Lac, 2003; Fourcaud et al., 2003a; Ancelin et al., 1999). This tool allowed the evolution of plant shape under its own weight to be calculated. This model took into account the active biomechanical reactions of trees, i.e., tropisms, due to the maturation strain differential involved by reaction wood appearance (Fournier et al., 1994). It was also possible to estimate the resulting field of growth stresses that is cumulated into the stem. However, the feedback simulation between biomechanics and growth has not yet been completed. At the moment, the influence of the plant's mechanical state on growth strategy is not considered. This phenomenon has been already discussed for root systems. Concerning the aerial part, it is admitted that mechanical stresses can modify the carbon allocation and allometric relations in the plant (Holbrook and Putz, 1989), but also the branching pattern as this is the case for epitonic plants for instance (Figure 5) (Crabbé, 1994). Mechanical stresses can impact also wood properties, i.e., density or reaction wood formation (Thibaut et al. 2001).

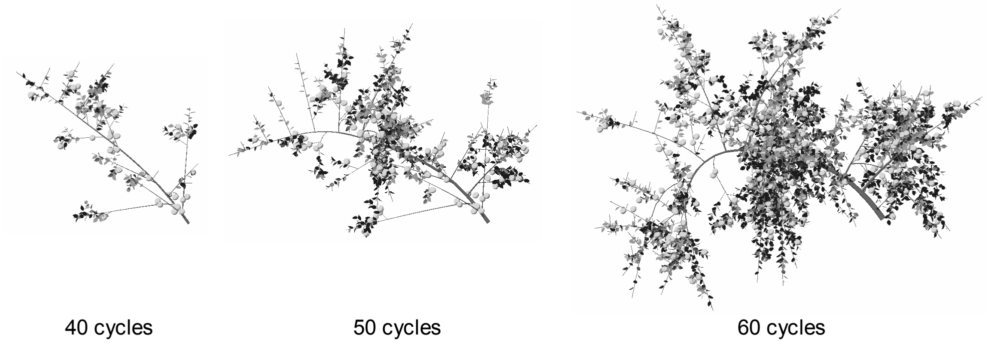
40 cycles 50 cycles 60 cycles

Figure 5: Simulation of an epitonic plant growth with AMAPmeca. Ramifications appear on the upper part of curved axes. This development mode is an example of using coupling between architectural models and biomechanics. (After Ancelin et al., 1999).

Future development of process based models must consider these biomechanical aspects, in particular for forestry applications (Cannell and Dewar, 1994). This improvement could indeed allow wood volume and wood quality to be estimated according to environmental variables. Biomechanical adaptation is also an important factor to consider when investigating risk of wind damage in forest stand.

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