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THE VENFOR PROJECT: INFLUENCE OF THE AERIAL ARCHITECTURE ON TREE SWAYING – AN EXPERIMENTAL APPROACH

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Abstract

This work focuses on qualifying the influence of the different crown elements on the mechanical behavior of tree submitted to time varying loading. For this purpose, dynamic tests were performed on three *Pinus Pinaster* Ait. seedlings. The aerial architecture of the trees was digitized. Crown spatial pattern varied significantly between the seedlings. In order to identify their intrinsic dynamic characteristics, the seedlings were submitted to free sway tests under different loading cases. The natural swaying frequencies that were measured did allow an assessment of the turbulent scale each structure is sensitive to. Anisotropy in trees' ability to dissipate energy absorbed from initial loading was observed. The tests also showed evidence that a secondary swaying mode was activated under specific loading. A couple of experimental subjects were tested at different phases of a progressive pruning with the purpose to weight participation of architectural elements in the dynamics of structures. Results showed that the needles had a critical role in damping process. Experimental data was sufficient to feed a numerical model and to proceed to further analyses on the influence of branching pattern in the mechanical tree stability.

Introduction

The trees may be considered as structures which are submitted to drag forces resulting from atmospheric flows, which are highly turbulent in and over stand canopies (Raupach 1988). Thus, they are submitted to dynamic actions (Papesch 1974, Mayhead and Oliver 1974, Mayer 1987, Wood 1995) since the turbulence. The natural swaying frequencies of the structure are excited when energy from airflow turbulent spectra is available at time scales close to those of tree motions (Gardiner, 1994). Such interactions may cause dramatic stresses in stem and in soil/root system. A static approach tends to underestimate the amplitude of stem displacements measured during strong gales (Kerzenmacher and Gardiner 1998). If the trees' sensitivity to gusts has been found to depend on their natural swaying frequencies, the importance of the dynamic effects should also be related to trees' ability to dissipate motion energy, namely the structural damping. Several damping mechanisms have been identified in the case of trees (Milne 1991). They include the wood viscoelastic behavior, the crown aerodynamic friction and the contact with neighboring trees. Other mechanisms less well qualified include behavior of the soil-root plate (England et al. 2000) and the oscillation of branches (Milne 1991, Moore 2002).
However the aerial system is not only involved in the damping process but also in the overall tree mechanics. When submitted to their own weight or to snow and wind loads, branches are applying bending moments to the stem. Then the variations in topological and geometric attributes (angle, position, number) of aerial elements are susceptible to modify stresses distribution in the stem. Features like torsion (Skatter and Kucera 2000) or streamlining also ap-

pear relevant to apprehend architectural development at a given time, in details and not in an integrated way, when studying tree mechanical behavior.
Thus, this work focuses on identifying the dynamic characteristics of different trees through an experimental approach. Explicit description of the crown elements of each tree was carried out prior to the dynamic tests in an attempt to link structure dynamics with aerial architecture.

Material and methods

Experiments were performed on three *Pinus Pinaster* Ait. seedlings, aged 4. The seedlings were growing in a forest nursery at latitude 44°73' N, longitude 0°68' W and altitude of 53 m. They were particularly chosen for an apparent contrast in their aerial system. Tree (T1) reached 2.57 m in height and 5.1 cm in diameter at 0.13 m from its base. Tree (T2) was 2.21 m high and stem diameter was 4.3 cm at 0.13 m from the base, with a stem which was significantly leaning locally at 0.32 m from the base. Its crown was asymmetrically developed with few branches in the North-East quarter. Tree (T3) reached 1.63 m in height and its primary axis stopped at 0.93 m from ground and forked into secondary axes. The diameter at 0.13 m was 5.7 cm. On every tree, the lowest branches appeared between 0.25 and 0.30 m from ground. Trees (T1) and (T2) were located at the edge of a small stand. Neighboring trees were either cut or pulled away in order not to affect the swaying motion. Tree (T3) was isolated and had no neighbors susceptible to intercept light or to affect its swaying.
Aerial systems were digitized in the end of July 2002 before any dynamic tests and any destructive measurements were carried out. Three-dimensional digitization was performed with Polhemus (Vermont, USA) 3D Fastrak® device linked to DIPLAMI software (Sinoquet et al. 1997), which allowed recording of the architecture directly in MTG format files (Godin et Caraglio 1998). These files allowed visualizing and analyzing the crown through numeric tools (AMAPmod® software, CIRAD, France). Measurement points included the diameter, the order of vegetative axis and the 3D coordinates of vegetative node. They were taken at locations of interest in the crown like: the beginning and the end of the vegetative axes, the beginning and the end of any zone with needles, every whorl and at the point of every change in local leaning of axes. The measurement allowed to state that the crown of tree (T1) was asymmetric. The sum of vegetative axes lengths for trees (T1), (T2) and (T3) were respectively 33 m, 44 m and 60 m. If 2^{nd} order axes summed lengths was appreciatively the same for each tree by reaching a mean value close to 19.1 m (0.8), these relatively accounted for two third, one half and one third of total length of axes with respects to the considered tree.
Free sway tests were carried out one month after digitization mainly because of required climatic conditions (no wind, no precipitations). The stem of each tree was equipped with three inclinometers: the first one was attached at 0.1m from ground, the second one at the third of tree height and the third one at half the tree height. Each inclinometer weighted 0.21 kg and registered rotations in two orthogonal and vertical planes with a sampling frequency of 10 Hz. Although we tried to decrease the inclinometers' influence on tree behavior by installing them in the lowest and stiffest part of the stem, it is likely that their mass affected the swaying of the trees. Reversible strain gauges were glued on core wood of some branches of Tree (T1) at 5 cm from their base (Fig. 1).
In order to study the influence of loading, the motion of the trees was initiated in different ways during the tests. In the first case of Initial Displacement (ID1), the stem was pulled away with a lightweight nylon rope from its equilibrium position, kept in this position for a few seconds until remnant sways in branches ceased and then the stem was finally released. The other way (ID2) consisted of pulling the stem three times in a row by trying to synchronize pulls with the first sways. In ID1 and ID2, the rope was attached at the whorl closest to the half of the tree height. For both methods, displacements were applied in two orthogonal directions which differed between trees. For each ID, tree, and direction, tests were reproduced four times except for tree (T3). This tree was tested only two times for each load case because of the arrival of wind gusts. A progressive pruning was performed on tree (T1) lead-

ing sequentially to the removal of needles, 3rd and 2nd order axes. This tree was tested in every intermediate phase as previously described. Those tests were performed in September 2002.

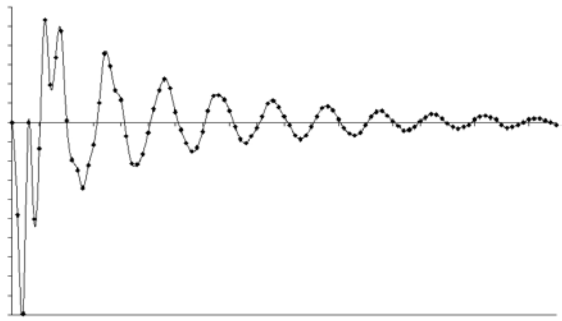
Figure 1: The tree (T1) through the different phases of pruning. 3 strain gauges were glued on 3rd order axes in a/, an inclinometer attached on the stem in b/. The first phase of pruning consisted in removing the needles (c/), then in removing the 3rd order axes (d/) and finally in removing the 2nd order axes so that stem (1st order axis) alone was left.

More tests were carried out on tree (T2) in the beginning of December 2002. ID2 was replaced by ID3 which consisted in pulling the stem at the top, waiting for branches to stop oscillating and then releasing it. The tree was progressively pruned with removal of its 3rd and 2nd order axes. However, the needles were left on the remaining axes at the different steps. The crown elements were weighted after their removal as for the pruning performed on tree (T1). We will be referring to the tree (T2) as (T2s) for results obtained in September and as (T2d) for those obtained in December.

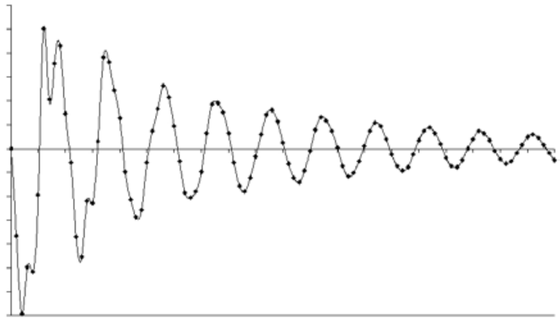
Results

The time series of stem motion showed a signal composed of two superimposed damped sine waves (Fig. 2). The first sine was lightly damped and characterized by a relative low frequency. Though the swaying frequency and damping ratio were found to differ between the trees, this signal was present in every response obtained. The second signal was of a higher frequency than the first one and of shorter duration as it was present only at the beginning of the response to ID. However, the amplitude of the second sine was minor compared to the amplitude of the first sine in the cases of ID 2 and 3 (Fig. 2b/ and 2f/). Consecutively to the removal of the needles, the second sine in time series of (T1) stem motion disappeared, and this for all cases of ID. The mass of the foliage was equal to 75 % of the crown mass and its removal lowered the mass center of (T1) from 0.98 m to 0.73 m. The removal of 3rd order axes on the tree (T2d) decreased the crown mass by 34 % and the mass center by 0.02 m. The higher frequency sine still appeared in stem sways. The second sine became negligible only after the removal of the 2nd order axes.
Strain records obtained from gauges placed on lateral and upper sides of the same branches gave signals with same frequencies. Yet, the responses corresponding to lateral and up-an-down flexions were out-of-phase. These results showed that one gauge is sufficient to measure the swaying frequency of any branch but not sufficient to evaluate 3D features like the branch trajectory. Every branch was found to oscillate with same frequencies that those

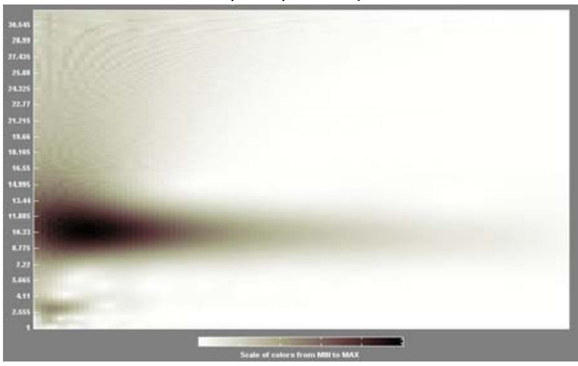
of the stem of (T1) when foliage was present. Both low and high frequency oscillations participated in branches' motions although the amplitude of low frequency motions was dominant. Once the foliage was removed from the tree (T1), high frequency motions dominated the swaying of branches while the stem was mainly swaying at a relatively low frequency. Moreover, the dominant frequency was found to differ between branches, ranging from 2.50 to 4.17 Hz. A third superimposed sine, with a frequency of 2.30 Hz, was recorded in the time series of branches below height of ID application. This sine might be connected to the second and weaker sine observed in stem sways whose frequency was also 2.30 Hz.



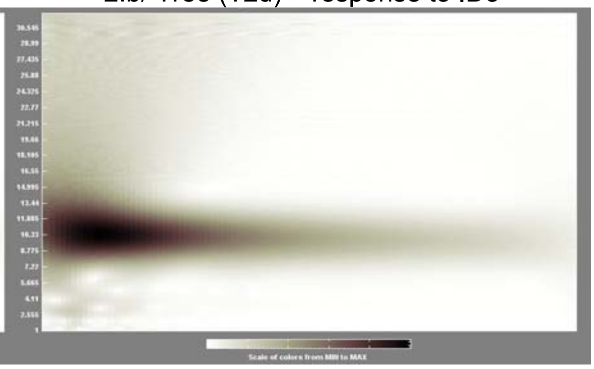
2.a/ Stem of (T2d) – response to ID1



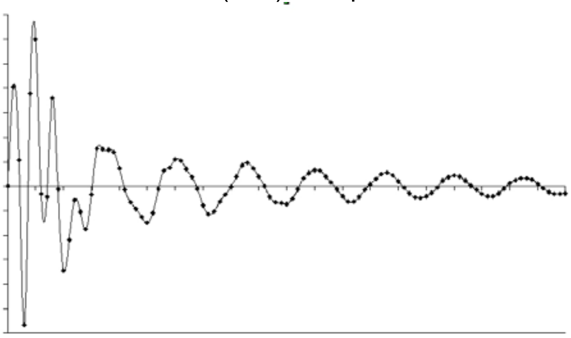
2.b/ Tree (T2d) – response to ID3



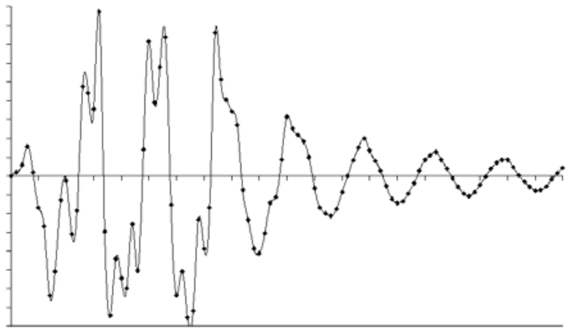
2.c/ Stem of (T2d) – response to ID1



2.d/ Stem of (T2d) – response to ID3

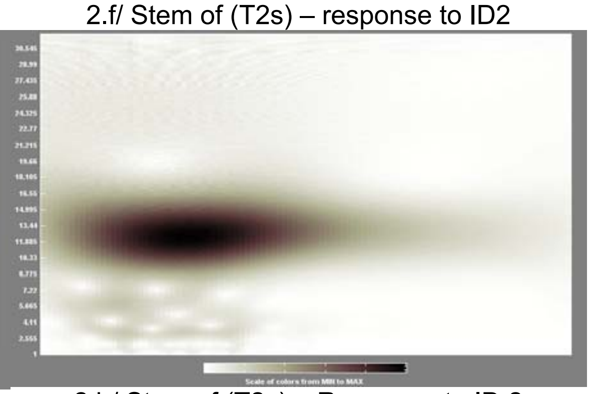


2.e/ Stem of (T2s) – response to ID1



2.f/ Stem of (T2s) – response to ID2

2.g/ Stem of (T2s) – response to ID1



2.h/ Stem of (T2s) – Response to ID 2

Figure 2: Times series and scalograms of (T2) stem motion. Each figure corresponds to 10 s of (T2) stem motion. Scalograms were obtained through Continuous Wavelet Transform. Mother wavelet was Complex Morlet Wavelet. For the time series, on the x-axis and rotation (°) is plotted on the ordinate axis. For the scalograms, time (s) is also plotted on the x-axis and the swaying period (s) is plotted on the y-axis. The gray levels correspond to the signal amplitude; the darker the shade, the higher the amplitude is at the considered time and swaying period.

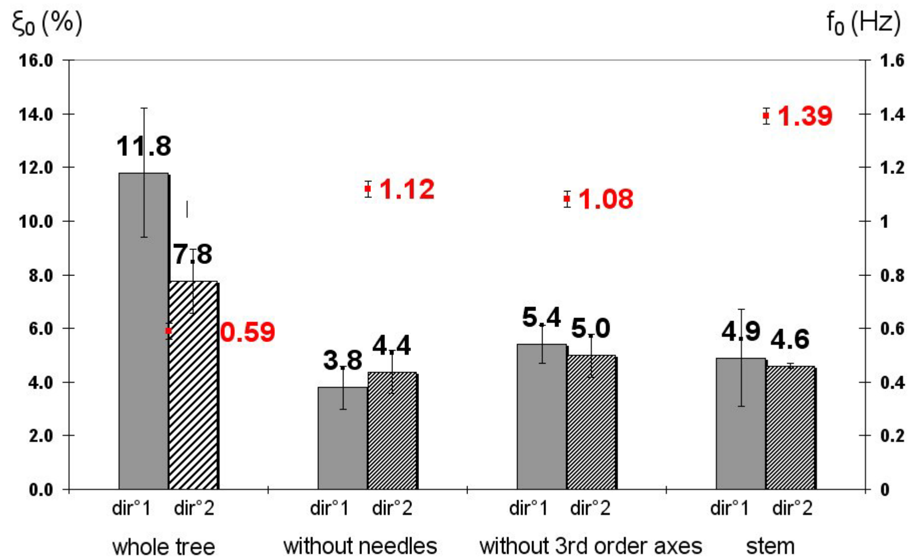
Data obtained from the inclinometer located at the first third of stem height.

For every tree in their natural state, the frequency, f_0, of the lowest frequency sine present in the response was not found to depend on ID direction nor to the way of its application (Tab.1). Damping ratio, ξ_0, was different depending on ID direction for trees (T1) and (T2).

		Case of ID	Tree (T1)	Tree (T2s)	Tree (T3)	Tree (T2d)
Direction 1	f_0 (Hz)	1	0.61 (0.02)	0.78 (0.02)	0.82 (0.02)	1.01 (0.02)
		2	0.59 (0.02)	0.77 (0.02)	0.81 (0.01)	-
		3	-	-	-	1.01 (0.02)
	ξ_0	1	0.122 (0.30)	0.050 (0.017)	0.041 (0.007)	0.042 (0.008)
		2	0.115 (0.018)	0.064 (0.015)	0.069 (0.012)	-
		3	-	-	-	0.054 (0.012)
Direction 2	f_0 (Hz)	1	0.59 (0.02)	0.76 (0.02)	0.80 (0.01)	1.03 (0.02)
		2	0.59 (0.02)	0.73 (0.02)	0.79 (0.01)	-
		3	-	-	-	1.04 (0.01)
	ξ_0	1	0.075 (0.011)	0.063 (0.015)	0.049 (0.004)	0.052 (0.011)
		2	0.080 (0.011)	0.079 (0.010)	0.058 (0.014)	-
		3	-	-	-	0.057 (0.005)

Table 1: Swaying frequency and damping ratio obtained from the measurements. Each value represents on the average of 4 tests except in the case of (T3), where each value represents an average of only 2 tests.

After the removal of the tree (T1) foliage, we measured an increase of f_0 by 90 % and a decrease of mean ξ_0 by 65 %. Since then, the anisotropy in damping was not observed anymore. Further removal of 3rd order axes led to a decrease of f_0 less than 4% and an increase of 21 % for ξ_0 compared to the previous phase of pruning. Final pruning of the 2nd order axes increased swaying frequency to 1.39 Hz. In the case of tree (T2d) case, the pruning of 3rd order axes increased the frequency of primary sways from 1.03 to 1.07 Hz for the stem and the mean damping ratio from 0.051 (0.011) to 0.059 (0.014) (notation is average value with standard deviation into brackets). The pruning of the 2nd order axes increased the frequency to 1.98 (0.03) Hz and decreased the damping ratio to 0.048 (0.004). Anisotropy of the damping ratio was conserved through pruning process of tree (T2d). Yet, it is worth noting that ξ_0 appeared with important deviations, which ranged from 8.2 % to 34 %. The highest deviation on f_0 did not reach 4%.



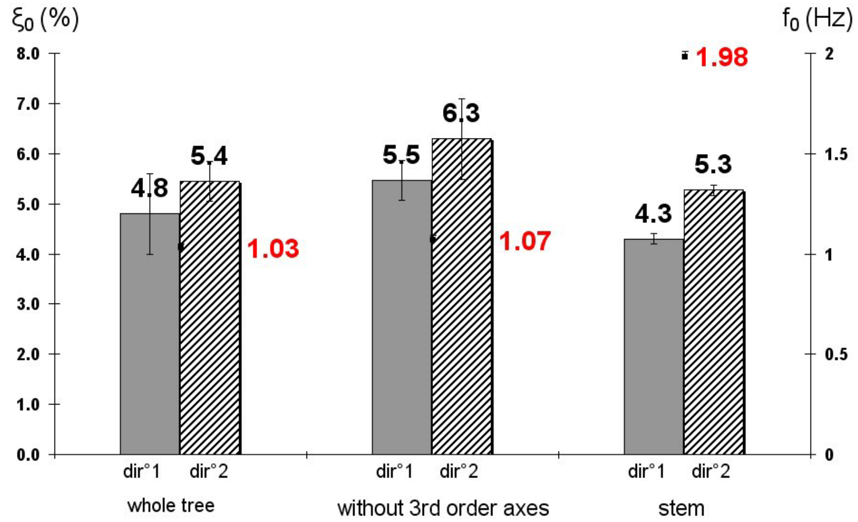


Figure 3a/ and b/: Evolution of dynamic characteristics during the pruning performed on the trees (T1) and (T2d). Bars represent average damping ratio for both ID directions (the left bar is for direction 1 while the right one represents direction 2). Plots represent the swaying frequency of the tree. Error bars represent Standard Deviation.

Discussion and conclusions

Every sine signal associated with a given frequency and present in the response of a structure to dynamic loading may be related to an oscillation mode of the element which has been excited (Clough and Penzien, 1975). In this experiment, the first mode, the one occurring at the lowest frequency, was not found to depend on the initial load applied to stem. Thus it might be considered as the dominant oscillation mode. However, it would not be accurate here to assume that this mode is the fundamental one without further studies since this mode involves at least compound bending. Tree sways were indeed not limited to a vertical plane but involved bending in both orthogonal directions. The main plane of bending changed constantly during the response to the initial displacement. In order to understand better the complex trajectory of the stem, the torsion needs to be studied.
The frequency of the first mode was found to differ for each of the tested trees. The difference was close to 30% between trees (T1) and (T2s) which had similar biomass height profiles and crown shapes. The difference was only 6% between trees (T2s) and (T3), trees which had different crown structures. Thus, it appears that an architectural viewpoint alone is not sufficient to evaluate the dynamic characteristics of the structure. Parameters including the soil-root behavior and the wood mechanical properties have to be included in order to assess the frequency of primary sways.
As already stated, the foliage removal caused a major increase (90 %) of the swaying frequency of (T1) stem. This removal came along with an important removal of crown mass and resulted in a lowered mass center. In the case of tree (T2), the pruning of 3^{rd} order branches, and then a third of crown mass, did not significantly alter the swaying frequency of the stem with an increase of only 4%. Such observations are consistent with the statement Moore (2002) who proposed that at least 80 % of crown mass has to be removed to induce a significant change in the swaying frequency of trees. Since this was proposed in the case of classical pruning, then there might be a need to introduce other factors than percentage of biomass removal, such as mass center position and its evolution, in order to study the efficiency of different pruning strategies.
Structural damping was found to depend on initial load direction for trees having branches asymmetrically distributed around their stems. The difference in damping was highest for the tree (T1) where load directions corresponded to directions where crown frontal areas were

maximal and minimal respectively. The difference was smaller for the tree (T2) where load directions and frontal area anisotropy did not match exactly. For the last tree, (T3), which had an axisymmetrical crown, the difference was not found to be significant. The anisotropy of damping might be due to the aerodynamic drag of tree since it appeared as connected to the anisotropy of branching pattern and to the presence of foliage, which is mainly responsible for the damping resulting from air friction.
Free sways tests allowed an identification of two important dynamic characteristics of the structures which are frequency and damping ratio. This experiment also showed that another swaying mode than dominant one might be excited under specific loading. It also showed the major role of foliage in the structure dynamics. However, the damping mechanism due to branch swaying was difficult to observe. The lack of ability to uncouple architectural factors from other factors through an experimental process indeed limited the study of the influence of branches itself. In order to isolate the relative influence of every factor, we are developing a numerical model of trees' dynamics. This model is designed for stability studies but also as an input for long-term adaptation to mechanical stresses (Fourcaud et al. 2003) that have to be considered in the simulation of tree growth.

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