Modelisation of the trunk daily diameter variation during wet season in a neotropical rain forest of French Guiana

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Abstract

Tree trunk diameter usually changes during the day and the night and along full year with both a rainy and a dry season. Aside of cambial growth, tree trunk diameter changes is the combination of successive layers contribution: purely passive mechanical strains of the heartwood, change in hydrostatic pressure in the sapwood and in the living phloem, changes in the maturation stress during the year and swelling or shrinkage of dead outer bark due to change in relative humidity of surrounding air.
Trees were equipped with home-made dendrometers and their diameters were measured daily and monthly almost 2 years with both a rainy and a long dry season. Change in tree trunk diameter is due to different phenomena those operated in different successive layers. On some species, no daily variation in the trunk diameter is observed even if large daily water fluctuations are observed.

Mechanical model based on coaxial cylindrical layers is developed and implemented in Matlab in order to highlights these variations. The model shows apparent strains variations synchronic with daily water variation. The effects of heartwood thickness on the tree trunk daily apparent strains variation make in evidence small apparent strains for high values of relative heartwood thickness that can explain the no daily variation in some species.

Introduction

Trunk variation can be pronounced in neotropical rainforest and the stem shrinkage, principally during the dry season [1], [2], [3], and [4]. Aside of cambial growth, tree trunk diameter changes is the combination of successive layers contribution. The function of the successive parts of the trunk section is rather different. Firstly, the bark (outer and/or inner) appears to be the main deformable **"elastic"** tissue in trunk [5] and potentially explain the great variations between dry and rainy seasons [2]. Roth in 1981 [6] observed a dilatation growth, which was very specific of the species. This phenomenon could occupy up to 70% of the entire bark width, and this was in axial and tangential direction. Secondly, the sapwood have primordial role for involved water to photosynthetic apparatus. The water content of this tissue is quite constant during the year. Sapflow is variable among species and fluctuate among the seasons [7]. Daily trunk fluctuation were caused by development of the tensions in the water columns of transpiring trees [8], by only the fluctuation of the bark [9] or by potential hydraulic connection between bark and sapwood [5] and [10]. The bark content more water than sapwood and the seasonal fluctuation is potentially more pronounced [3]. The daily and seasonal fluctuations of the bark could also be explicated by the air humidity [9]. The bark is the thinnest and the wettest tissue. Its external position contributes to its climatic dependent variation [11]. The bark sensitivity of the climatic variations was already exposed and could explain also the trunk variation [9; 11; 13]. Compared with the sapwood, the heartwood appears to be relatively limited in terms of effective water storage. Heartwood formation results from numerous physiological and biological changes, including the death of any living cells and, with some exceptions, a decline in water content. Moreover, seasonal

variation in water content is generally much less pronounced in the heartwood than in the sapwood [11].

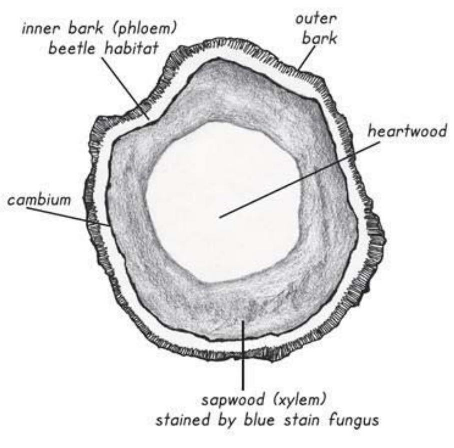
Information on the relative contributions of different stem tissues to daily and seasonal changes in diameter is scarce in tropical rainforest. Experiments were performed in-situ to measure these variations at Paracou in French Guiana. Trees were equipped with home-made dendrometers and their diameters were measured daily and monthly almost 2 years with both a rainy and along dry season. A diminution in tree trunk diameter was observed in dry season in spite of the radial growth due to the cambium activity and a large augmentation was observed in the onset of rainy season. In addition, daily variation in the trunk diameter was observed on some species, but not on some other species even if large daily water fluctuations are observed, in dry and wet season [7]. This is the case of the Vantanea sp for which circumference variation was very stable and not synchronic with the water status (Figure 2b, red curve).

A mechanical model is performed to explain the experimental observations. The transverse section of the tree trunk is modelled as multi-layered coaxial cylinders. The layers are the tissues including heartwood, sapwood, inner bark (living phloem) and outer bark (non conductive phloem and cork). We focus on daily variations in wet season such as the only daily variation is the sapwood hydrostatic pressure dues to the circulation of the xylem. The exterior air relative humidity is always high so the bark moisture content stands over the fibre saturation point and daily bark shrinkage is null or negligible.

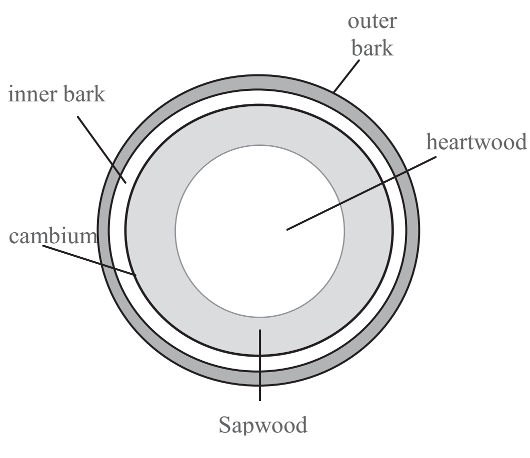
Mechanical formulation: coaxial-cylindrical model:

Problem position

A transverse section of tree trunk is composed of different layers (Fig. 1a). In addition to dimensional variation of tree trunk due to growth by the cambium, under water tension in the sapwood and the inner bark, and the variation of the humidity of external atmosphere, tree trunk observe variation of its diameter. So, first tree trunk can be idealized as a cylindrical structure (Fig.1b) having a different material proprieties in each layer.
In mechanical point of view, the problem consists in computing the state of equilibrium of cylindrical structure composed of different layers of orthotropic material, and subjected to an internal stress and an external constraints at its borders.



(a) Transverse section of tree trunk



(b) Cylindrical structure

Fig. 1 (a) Tree trunk section (b) cylindrical model

Formulation of the mechanical problem

For a mechanical analysis of a dimensional variation of a tree trunk, the complete model must include all the equations of the mechanics, especially equilibrium, constitutive equations, and boundary conditions. Under the internal and external actions considered in this paper (hydrostatic pressure principally) and an hypothetic regular cylindrical structure, the displacement, strain and stress fields generated are only radial dependent, in addition, no shear stresses and no shear strains occurs in the tree trunk. All these considerations simplify the mechanical equations.

In the following, we first briefly remind the essential of the mechanical equations of an homogenous cylindrical layer and then, present solutions for a multi-layer structure. So, let's consider an adequate cylindrical system (R, T, L), where R, T and L are radial, tangential and longitudinal directions respectively. At a given radial position r, the induced displacement vector and associated strains and stresses are respectively represented by the following vectors.

$$\underline{u} = u_R, u_T, u_L \quad , \qquad \underline{\varepsilon} = \varepsilon_R, \varepsilon_T, \varepsilon_L \qquad \text{and} \qquad \underline{\sigma} = \sigma_R, \sigma_T, \sigma_L$$

Where strains components are given by:

$$\varepsilon_R = \frac{du_R \ r}{dr} \qquad \text{and} \qquad \varepsilon_T = \frac{u_R \ r}{r} \tag{1}$$

u_R and ε_R are radial displacement and strain and ε_R and ε_T are tangential displacement and strain.

Wood is commonly modelled as an orthotropic linear elastic material [14]. In our case, the constitutive law is restricted to this relation:

$$\underline{\sigma} = \underline{\underline{C}} \cdot \underline{\varepsilon} + \underline{\beta} \qquad \text{where} \qquad \underline{\underline{C}} = \begin{bmatrix} C_{RR} & C_{RT} & C_{RL} \\ C_{TR} & C_{TT} & C_{TL} \\ C_{LR} & C_{LT} & C_{LL} \end{bmatrix} \tag{2}$$

$\underline{\underline{C}}$ is the behaviour tensor and $\underline{\beta}$ is the initially induced stresses vector, that is relate in our case to hydrostatic pressure in the sapwood and inner bark. It is given by: $\underline{\beta} = \beta_R, \beta_T, \beta_L$.

Equilibrium equations are restricted to the following equation:

$$\frac{d\sigma_R}{dr} + \frac{\sigma_R - \sigma_T}{r} = 0 \tag{3}$$

Equilibrium equation can be expressed in displacement term by combining behaviour law, equation (2), strains expressions given by equation (1) with equilibrium equation (3). It is given by:

$$r\frac{d^2u_R}{dr^2} + \frac{du_R}{dr} - \gamma^2 \frac{u_R}{r} = \kappa \tag{4}$$

Where $\gamma^2 = \frac{C_{RR}}{C_{TT}}$ and $\kappa = \frac{\beta_T - \beta_R}{C_{RR}} + \frac{C_{TL} - C_{RL}}{C_{RR}} \varepsilon_L$

The general solution of equation (4) is [2]:

$$u_R \ r = Ar^{\gamma} + Br^{-\gamma} + r\frac{\kappa}{1-\gamma^2} \tag{5}$$

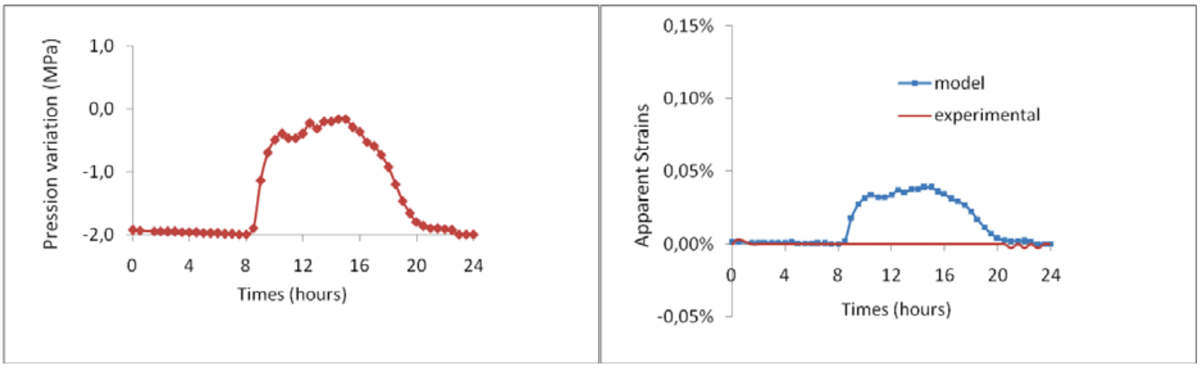
A and B are integration constants. Their values are determined using the boundary conditions of the problem. The strain field can then directly derive from equation (1) and the associated stress field from the constitutive law given by equation (2).

Multi-layered model

The formulation is extended to a cylindrical layered structure composed in our case of 4 layers numbered 1 to 4 from the inside of the cylinder. When writing equation (5) for each layer, and when considering interface and boundary conditions, we obtained 9 equations with 9 unknown parameters (8 unknown integration constants and longitudinal strain ε_L). These equations form a linear system. A Matlab program based on this cylindrical formulation was realized to resolve the linear system and to compute all displacement, strain and stress fields through tree trunk transverse section. This model was initially formulated by Alméras and Gril [15; 16]

Results and discussion

Daily water status and apparent strains measured in-situ are illustrated in figures (2a and b curve red) for the Vantanea sp in wet season (se table 1). Large daily fluctuations are observed but the measured circumference was very stable and not synchronic with the water status. Figure (2b, blue curve) shows apparent strains daily variation given by the model in wet season. In opposition to the experimental observations, the apparent strains daily variations given by the model are synchronic with the water flow. This result is expectable as the model just takes in account different layers rigidity.



(a) (b)

Fig. 2: (a) Daily variation of water status, (b) apparent strains for Vantanea sp. In wet season.

The effect of heartwood thickness on the apparent strains variation given by the model (Figure 3) shows a rapid diminution of the apparent strains with the heartwood thickness for relative thickness values above 20%. Most of the considered species relative had a heartwood thickness above 80% (see table 1). So, as compare to small trees with few heartwood as often described in the literature, the daily apparent stains variation given by the model is nearly 10 times less due to the effect of heartwood compensation of the sapwood swelling or shrinking. Then the measurements in strain values (diameter growth divided by tree diameter) should be 10 times more accurate than for small trees, which was not the case in this experiment.

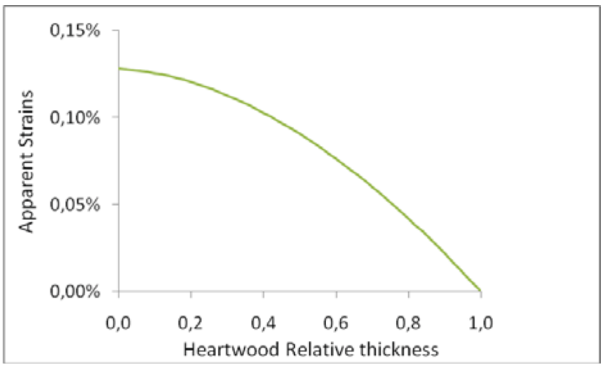


Fig. 3: Daily apparent strains variation with heartwood relative thickness.

Table 1 Relative thickness of different layers of species from Paracou – French Guiana

Species	Familly	radius	Thickness (mm)			Relative thickness (%)		
			Bark	Sapwood	Heartwood	Bark	Sapwood	Heartwood
Dicorynia guianensis	Caesalpiniaceae	202.95	3.5	19.635	179.8	1.72	9.67	88.59
Dicorynia guianensis	Caesalpiniaceae	163.05	3	32.95	127.1	1.84	20.21	77.95
Dicorynia guianensis	Caesalpiniaceae	172.65	2.5	32.62	137.5	1.45	18.89	79.64
Goupia glabra	Celastraceae	394.25	6.75	61.15	326.35	1.71	15.51	82.78
Licania heteromorpha	Chrysobalanaceae	112.45	2	7.295	103.2	1.78	6.49	91.77
Recordoxylon speciosum	Caesalpiniaceae	223.85	3.5	7.085	213.25	1.56	3.17	95.26
Slonea sp	Eaeocarpaceae	234.85	5.5	21.885	207.45	2.34	9.32	88.33
Vantanea sp	Humiriaceae	201.05	5	39.27	156.8	2.49	19.53	77.99
Oxandra asbecki	Annonaceae	82.6	1	7.515	74.1	1.21	9.10	89.71
Vouacapoua americana	Caesalpiniaceae	139.8	1.25	6.165	132.4	0.89	4.41	94.71

Conclusion

Change in tree trunk diameter is due to different phenomena those operated in different successive layers. In addition, on some species, no daily variation in the trunk diameter is observed even if large daily water fluctuations are observed.

Mechanical model based on the analytical cylindrical model initially by Alméras and Gril is implemented in Matlab routine, and used to explain the experimental observations by the tree trunk transverse structure and the phenomena those operate at different layers. Contrarily to the experimental observation, the model shows fluctuations of the apparent strains synchronic with the water pressure in the sapwood. But the model also shows that apparent strains strongly decrease for high heartwood relative thickness. So the no daily apparent stains variation observed in some species can be explained by both the effect of heartwood compensation and the lack of precision of dendrometers.

It will be interesting to verify this model on trees with different heartwood thickness ratios, in the wet season. Then the model could be used to explain the role of external bark shrinkage durin dry season on the surprising diameter decrease of some species in that period.

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