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Measuring local and global vibration modes in model plants

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ABSTRACT

Model plants are extensively used in biological studies, and their mechanical behaviour needs to be better understood, in relation to studies in mechanoperception for instance. We present here the first approach to derive experimentally the modal parameters of two of these plants, *Arabidopsis thaliana* and *Populus tremula* × *alba*. A classical sinusoidal sweep excitation is used, with a measurement of displacements based on LKT optical flow tracking, followed by a bi-orthogonal decomposition (BOD). This allows us to estimate several modal frequencies for each plant, as well as the corresponding spatial localizations of deformation. Analyzing the modal frequencies, we show that global and local modes correspond to distinct ranges of frequencies and depend differently on plant size. Possible phenotyping applications are then discussed.

1. Introduction

Plant biomechanics addresses issues related to a very large variety of organisms, from spores to trees, and takes both fundamental and applied points of view. In the development of plant biology, model plants play a key role as they allow to focus fundamental or applied studies on genomically sequenced organisms. Two of these model plants, *Arabidopsis thaliana* and *Populus tremula* × *alba* (referred to as At and Pt in the following) are often considered in fundamental biology studies where mechanical issues are involved [1]. Unfortunately, whereas these model plants are known in great detail in terms of genetics [2], little is known of their mechanical behaviour. To investigate issues such as the perception of deformation by plants (thigmomorphogenesis [3]) it becomes necessary to have a good view of how a plant deforms under external load. More precisely, vibrational characteristics such as modal frequencies are largely unknown, while the dynamic response to excitations such as wind is known to affect growth.

In parallel, the dynamics of other plant species such as trees or crops have been extensively studied, see for instance [4]. Generally only the first mode of vibration has been measured and modelled. This fundamental mode is known to carry a large part of the response to wind, but higher frequency modes have also been shown to play an important role in dissipation of motion [5]. This led recently to several experimental and theoretical studies on the multimodal dynamics of these multi-branched systems such as trees. One of the key recent results was that these higher modes are localized in

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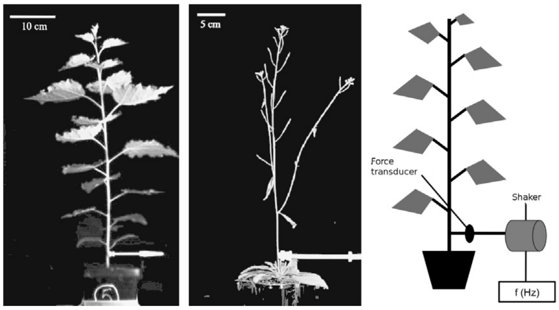

Fig. 1. Model plants and experimental set-up. Left: Young poplar *Populus tremula* × *alba*, denoted Pt in the text. Centre: Floral stem of *Arabidopsis thaliana* denoted At in the text. Right: schematic view of the excitation by the shaker.

space [6], a living illustration of the general concept of localization of branched systems [7]. For crops, such as wheat or alfalfa, little is known outside their fundamental mode of vibrations [8,9].

At the growth stage where they are studied by biologists, model plants such as Pt or At do not have the same geometrical characteristics as fully grown trees which have up to eight orders of regular branching. They however display very contrasted shoot architecture with different level of mechanical heterogeneities: young Pt trees used as model plants are made of a straight stem with large leaves, with the apical part (referred to as "apex" in the following) being made of much more compliant and soft tissues (Fig. 1, left). In contrast, At plants, at the inflorescence stage, are generally composed of a few leaves close to the ground (with little possible deformations), but develop a branched floral stem (inflorescence) that is slender and subjected to deformation, see Fig. 1, centre. Note also that for biological studies, both At and Pt are usually grown in pots, with substrates (i.e. artificial soil) of weak cohesion.

Measuring the modal properties, such as frequencies and modal shapes, of such systems is a challenge. For large trees, standard modal methods of modal analysis have been used, such as excitation by pull and release or hammer impact, with accelerometers or strain gages, see [4]. Here, in small model plants, tissues are soft, organs are very light, and the mechanical experiments should not be destructive or too invasive. Using a shaking table must be avoided because of the softness of the soil. Moreover, because of the large variability in geometry among plants of a given species at a given age, only statistical results have some meaning. This implies that a large number of experiments is undertaken, and therefore that the method used has to be simple enough.

The aim of the present paper is to present a new approach to measure modal quantities in such systems, and to give a first interpretation of the results in terms of potential localization of the modes and frequencies. The further application of this technique will also be discussed.

2. Materials and methods

2.1. Plants

We consider two sets of plants, the young Poplar *Populus tremula* × *alba* and *Arabidopsis thaliana* at the stage where it develops a floral stem. More precisely, hybrid polars (*P. alba*×*tremula* clone INRA 717-1B4) were obtained by *in vitro* micropropagation and grown on nutrient solution [10]. These trees were grown in a greenhouse with controlled temperature and irrigated by subirrigation. The experiments are conducted on seven young unbranched poplars (Fig. 1, left) taken at different stages of growth with total heights between 18 cm and 100 cm. The *Arabidopsis thaliana* plants were grown in a greenhouse under a 16 h light/8 h dark regime at 21°C, 55% relative humidity (Fig. 1, centre). A set of 24 At plants was used. The height of the main stem varied from 10 cm to 25 cm. These two sets of plants are kept under standard thermal conditions during the vibration experiments, by using low-temperature LED lighting for the visual acquisition.

2.2. Excitation

The proposed method is based on a sinusoidal excitation, with a slow sweep in frequency. Each plant is excited by a shaker attached close to the base of the stem (Fig. 1, right). The shaker (*PCB Piezotronics*, *K2007E01*) is controlled by a low-frequency generator (*AIM-TTI, model TG2000*). For most tests on Pt, the applied load was measured by a force transducer (*PCB Piezotronics*, *288D01SN2715*). Sweeps of 2 Hz, lasting 30 s, are used. The range of sweeps was chosen such that no more than one mode is found in a given sweep. As Pt and At have quite different masses and stiffness, the excitation has to be adapted in terms of frequency range: Pt plants were stimulated between 0 and 36 Hz (18 sweeps), and At ones between 0 and 24 Hz only (12 sweeps). The level of excitation, of the order of 0.1 N, was also adapted to have small amplitude of motion, yet measurable. As only linear modal characteristics are sought, the magnitude of the force does not affect the results.