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Review

Oscillation damping in trees

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ABSTRACT

Oscillation damping is of vital importance for trees to withstand strong gusty winds. Tree adaptation to wind loading takes place over a long time and during a storm only passive damping mechanisms can reduce the impact of the wind on trunk and roots. Structural damping, a phenomenon, which is associated with the conspicuous movements of the branches relative to the trunk is of particular importance. Primary and higher order branches can be seen as multiple tuned mass dampers. Moreover, as the frequency bands overlap within branches and between primary branches and the entire tree, resonance energy transfer can distribute mechanical energy over the entire tree, such that it is dissipated more effectively than in a tree with stiff branches and not so much focused on the tree trunk and the roots.

Theoretical studies using modal analysis and finite element methods have supported these assertions. Next to "multiple mass damping" and "multiple resonance damping", both characterized by linear coupling between the elements, a third non linear mode, operative at large amplitudes has been identified: "damping by branching". In all these not mutually exclusive concepts frequency tuning between the elements appears to be a fundamental requisite.

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1. Introduction

"Life in Moving Fluids" [1] provides a comprehensive description of the biological implications of hydrodynamics. Wind forces are the most critical forces that a land plant has to withstand [2,3]. The mechanical stability of trees under static wind loads has been reviewed [4]. It is particular important that trees and other plants can react to wind in a flexible manner. Stem and branches bend towards the lee side. This "streamlining" [5–8] leads to a significant reduction of the sailing area and to some extend also to the drag coefficient. Leaves also reconfigure alignment in the wind, which further reduces drag [9,10].

Static wind can only be realized in wind tunnels. In reality wind is always dynamic with a broad range of frequencies [11–13]. Trees and other plants are, therefore, likely to be excited to sway

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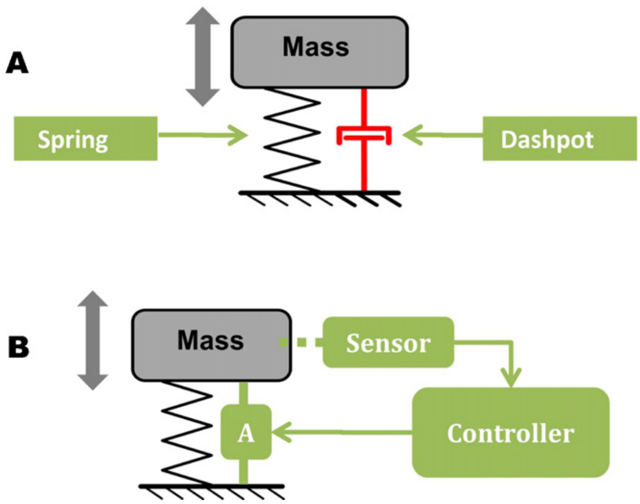

Fig. 1. Schematic representation of different principles for oscillation damping. (A) passive damping by dissipation of energy in a dashpot (compare the Voigt/Kelvin model for viscoelastic materials [20]). (B) active counteraction requiring a sensor, a controller, and an actuator A.

[11,14–19]. Unless these oscillations would be damped, a "resonance catastrophe" could lead to stem breakage or uprooting.

If friction among different plants or among different side organs [16,19] and friction in the root soil system are set aside, there are two principle sources of oscillation damping. Mechanical energy imposed by gusty winds can be converted to heat by viscous damping in the material, or it can be dissipated to the surrounding fluid, i.e., aerodynamic damping [20]. Branches can often be seen not to sway in line and in phase with the trunk of a tree, particularly in strong gusty winds. As discussed in sections 3.1 and 3.2, experiments show that this leads to an amplification of viscous damping as well as of aerodynamic damping, referred to as structural damping [21]. Three, not mutually exclusive, concepts have been proposed to describe this phenomenon: tuned mass damping [22,23], resonance energy transfer [24], damping by branching [25]. These concepts will be delineated in detail in Sections 3.2, 4.2 and 4.4.

2. Technical applications of oscillation damping

Under conditions of dynamic mechanical loads, which may result from gusty winds, water waves, or even from earthquakes, oscillation damping is of vital importance for the stability of trees or man-made structures. It is also an important aspect of posture control and control of movements [26]. There are several mechanisms by which unwanted or even potentially dangerous oscillations can be minimized: dissipation of mechanical energy, passive counteraction combined with energy dissipation, active counteraction.

These principles can be illustrated by the way they are applied in architecture and mechanical engineering (Fig. 1). Dissipation of energy is usually accomplished by a combination of springs and shock absorbers often referred to as dashpots. A car with malfunctioning shock absorbers will be dangerously unstable on bumpy roads. A well-known example of the application of passive counteraction is the Taipeh tower at Taipeh, Taiwan. As a tuned mass damper a 660 ton spherical body is suspended on steel cables and equipped with hydraulic dampers, such that it acts as a damped pendulum which swings with the same frequency as the entire building but with a 180° phase shift. This way it counteracts swaying of the building induced by the frequent earthquakes and yearly typhoons in this region. Other examples of passive counteractions are tuned mass dampers on tall chimneys or on wide span constructions such as the London Millenium Bridge or electric power lines.

Anti rolling tanks in ships were developed as early as 1889. The ship is equipped with two water tanks above the water line, one on each side. The tanks are connected by pipes, such that water can flow back and forth from one side to the other. This counteracts rolling movements of the ship. Tuning the filling of the tanks and the size of the pipes to the eigenfrequency of the ship, a 180° phase shift is attained, while dissipation of energy occurs via the flow of water through the pipes.

Alternative designs to reduce rolling in ships are automatically operated fin stabilizers localized below the water line. Such an active counteracting device requires sensors and actuators steered by a feed back controller (Fig. 1), or more advanced feed forward computing system. An active anti-roll stabilizer is also incorporated in some technically high quality cars.

3. Experimental work

3.1. Pull and release experiments

Earlier observations of conifer tree sway and oscillation damping after pull and release tests, have been reviewed [27]. The pull and release experiments on 26 years old Sitka spruce trees are particularly noteworthy: sway studies predicted that there is more aerodynamic drag than expected from wind drag studies, even when the influence of interference of branches with those of neighboring trees and viscous damping in the stem was subtracted [16]. A linear dependence of the damping ratio on the relative velocity was found in Norway spruce trees that was attributed it to viscous damping alone [28]. However, it should be considered that aerodynamic damping follows an exponential law with an exponent somewhere between 1 and 2 due to streamlining [5–8], such that it is difficult to separate the contributions of viscous and aerodynamic damping from a sway decay curve alone.

In pull and release tests on a young Douglas-fir tree viscous damping in the debranched stem amounted to 13% and aerodynamic damping for maximally 20%, (calculated on the basis of photographs in the direction of sway of all branches, but for a supposed rigid structure), such that structural damping accounted for two thirds of the overall damping observed for the intact tree [24]. Apparently the flexibility of the branches allows for an effective oscillation damping. Pull and release experiments were also carried out on deciduous trees [29]. In experiments on Bradford pears, leaves were shown to contribute significantly to oscillation damping [30]. Prior to these studies structural damping [21] was observed in pull and release experiments on *Arundo donax* [31,32].

3.2. Observation of tree sway

An alternative experimental approach is to record tree motion with a set of sensors distributed over the tree trunk and the branches in conjunction with monitoring wind speed and its direction in the immediate vicinity [11,13,15,33]. Natural sway frequencies and damping ratios of intact, partially debranched, and fully debranched Douglas-fir trees were measured [34]. The results suggested that branches should not be viewed as a series of masses lumped to the stem, but rather as individual damped harmonic oscillators coupled to the stem (compare [18]). This was confirmed after observing a high degree of damping during natural sway of conifers, two eucalypts and a palm tree under conditions of strong winds [23]. The high damping efficiency was explained to result from the dynamic sway of the branches with respect to the trunk referring to the concept of multiple mass damping (Fig. 2).