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Tree Biomechanics Literature Review: Dynamics

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Abstract. Tree biomechanics studies using dynamic methods of analysis are reviewed. The emphasis in this review is on the biomechanics of open-grown trees typically found in urban areas, rather than trees in forests or plantations. The distinction is not based on species but on their form, because open-grown trees usually grow with considerable branch mass and the dynamic response in winds may be different to other tree forms. Methods of dynamic analysis applied to trees are reviewed. Simple tree models have been developed to understand tree dynamic responses, but these largely ignore the dynamics of branches. More complex models and finite element analyses are developing a multimodal approach to represent the dynamics of branches on trees. Results indicate that material properties play only a limited role in tree dynamics and it is the form and morphology of the tree and branches that can influence the dynamics of trees.

Key Words. Biomechanics; Dynamics; Modes; Open-grown Trees; Urban Trees; Wind.

The biomechanical studies on trees that have taken a dynamic approach to their analysis are reviewed in this paper. Studies published in the last 20 years are mainly considered, with older, seminal studies included where appropriate. The field of biomechanics is often broken into two complementary approaches: statics and dynamics. Both methods are useful in studying the structure of trees under mechanical loading. This review of tree dynamics is part of a project on tree biomechanics that includes a review of tree statics presented as a separate paper (Dahle et al. 2013, *in review*).

This paper includes an introduction to biomechanical studies of trees; a review of the main literature on tree dynamics; the different dynamic methods of analysis that have been used on trees, including approaches used in forestry, urban forestry, and wind tunnels; and a summary of the complex multimodal studies that consider both tree and branch dynamics. The final section presents research on tree dynamics that is indicating how the form and morphology of trees influences the dynamic response in winds because the branch dynamics can be important.

The emphasis in this review is on the biomechanics of open-grown trees rather than trees in forests or plantations. The distinction is not based on species, but on their form, because open-grown trees, both excurrent and decurrent, usually have considerable branch mass. The term open-grown trees is used rather than urban trees, because the biomechanical principles are not unique to urban trees but rather to all trees of the open-grown form.

Despite the abundance of literature describing the interaction of wind and trees, particularly as it relates to tree dynamics (Moore and Maguire 2004; de Langre 2008; Gardiner et al. 2008; Sellier et al. 2008; de Langre 2012), the literature is almost nonexistent regarding recommendations for pruning open-grown trees to reduce wind damage (Smiley and Kane 2006; Gilman et al. 2008a; Gilman et al. 2008b; Pavlis et al. 2008). Therefore, this review concludes with a list of perceived knowledge gaps in the field of tree biomechanics.

Biomechanical Studies of Trees

Biomechanics applies the basic principles of structural engineering theory to the study of plant forms, including trees. A fundamental premise is that plants cannot violate the laws of physics (Niklas 1992). Biomechanics studies trees as mechanical objects (de Langre 2008), using engineering and physical principles in an attempt to understand the structural properties of trees and how they interact with the environment. The growth rate of trees is largely determined by physiological constraints, particularly those affecting photosynthesis and water transport. But regardless if these are optimal, tree size and shape are still limited by biomechanical constraints (Spatz and Bruechert 2000). Wood in trees is flexible and behaves as neither an ideal solid nor an ideal fluid (Vogel 1996). Wood and most plant materials are described as viscoelastic because their mechanical properties are both elastic and viscous (fluid like). These properties result in non-linear behavior (Miller 2005), and under mechanical loading, plant material does not act like steel or concrete and may not conform exactly to current mechanical models. For this reason it is important to be aware of the limitations of trying to get an exact value for a plant parameter, and to recognize when theory and reality fail to coincide (Niklas 1992). Furthermore, biological materials acclimate and can change their material properties as they age and grow (Lindström et al. 1998; Lichtenegger et al. 1999; Reiterer et al. 1999; Brüchert et al. 2000; Spatz and Brüchert 2000; Lundström et al. 2008; Dahle and Grabosky 2010b; Speck and Burgert 2011), so the dynamic responses can be difficult to predict.

Dynamics and Trees

Wind exerts the largest dynamic forces on trees and is the most important factor for dynamic loading on plants in the terrestrial environment (Niklas 1992). Tree response to wind is ultimately a dynamic process (de Langre 2008), and although understanding the static behavior of trees provides a good basis for understanding their overall behavior, it is a simplification of reality (Moore and Maguire 2004). One of the main reasons for studying trees in winds is to assess their stability and some of the earliest studies recognized that windthrow is also a dynamic process (Coutts 1986).

A dynamic analysis is more complicated than a static analysis because it includes all the static forces and additional components of inertial forces due to the motion, the damping forces and the dissipation of energy, the displacement and phase differences, the natural frequencies, and the consequent changes in motion (Den Hartog 1956). A force applied in a static manner will result in a deflection of a certain magnitude. The same force applied in a dynamic or cyclic manner, at a certain frequency, may increase or amplify the motion and produce a larger effect than the same force applied statically. This effect is called the dynamic amplification factor (DAF) or the dynamic response factor (DRF) and has been applied to trees in only a few studies (Sellier and Fourcaud 2009; James 2010; Ciftci 2012; Ciftci et al. 2013).

Open-grown Trees

The shape or morphology of the tree and the distribution of oscillating branch masses becomes important during dynamic studies (Rodriguez et al. 2008; Sellier and Fourcaud 2009; Ciftci et al. 2013). Slender forest conifers sway in a relatively simple manner, whereas open-grown trees, with many independent and larger branch masses, sway in a complex manner that is different from forest conifers and not yet fully understood (James et al. 2006). The dynamic interaction of branches in winds can significantly modify the frequency and damping of a tree (Moore and Maguire 2005).

Dynamic studies of trees aims to understand how individual trees respond in winds (Baker and Bell 1992; Roodbaraky et al. 1994; James et al. 2006; Kane and Smiley 2006; Baker 1997; Castro-Garcia et al. 2008; Kane et al. 2008; Kane and James 2011; Ciftci 2012) with a few studies investigating the effect of pruning on wind loads (Smiley and Kane 2006; Pavlis et al. 2008; Gilman et al. 2008a; Gilman et al. 2008b; James 2010; Ciftci et al. 2013). Studies examining tree failure due to winds in urban areas have been undertaken after wind storms (Duryea et al. 2007; Lopes et al. 2007; Kane 2008; Matheny and Clark 2009) but with only limited correlation to actual wind velocity and gustiness.

MAIN LITERATURE AND CONFERENCE PROCEEDINGS

Tree Dynamics

There have been several reviews on trees and wind, but they are mainly focused on forest trees (Moore and Maguire 2004; de Langre 2008; Gardiner et al. 2008). A bibliography for tree care professionals was published by Cullen (2002a). Moore and Maguire (2004) reviewed the concepts and dynamic studies by examining the natural frequencies and damping ratios of trees in winds. Gardiner et al. (2008) reviewed the mechanistic modeling of forest trees and the risk of damage in plantations. De Langre (2008) reviewed the literature on plants and examined the more complex fluid mechanics and multimodal models that are being developed to describe the complex dynamic responses of plants and trees. While not exclusively on dynamics of trees, there have been several major conferences on wind and trees that have published proceedings or books with contributions from many authors (Coutts and Grace 1995; Ruck et al. 2003; Mitchell 2007; Mitchell 2008; Schindler et al. 2012) and also conferences on plant biomechanics (Telewski et al. 2003; Salmen 2006; Speck and Burgert 2011; Moulia and Fournier 2012; Thibaut 2012). The first urban tree biomechanics conference was held in Savannah, Georgia, U.S. (Smiley and Coder 2002).

Winds and Tree Damage

Wind data can be expressed in a number of ways, including scales, such as the Beaufort Scale, and more commonly as wind speeds that use a variety of units (e.g., miles per hour, kilometers per hour, knots, m s^{-1}). This can be an obstacle to disseminating knowledge and for practical tree risk management (Cullen 2002b). Instantaneous wind speed is usually not available, and it is customary to quote an average wind speed (either 10-minute or one-hour average) and a gust wind speed taken as a three-second average (Holmes 2007). The wind speed at which tree failure begins to occur is defined in forest studies of trees as the critical wind speed (Oliver and Mayhead 1974; Petty and Swain 1985; Coutts 1986; Blackburn et al. 1988; Peltola and Kellomaki 1993; Hedden et al. 1995; Peltola 1996b; England et al. 2000; Gardiner et al. 2000; Zhu et al. 2000; Cullen 2002b; Zeng et al. 2007; Gardiner et al. 2008; Schelhaas 2008; Wood et al. 2008). Mechanistic models in forestry research use the critical wind speed value to calculate the percentage of failure likely to occur in a forest stand and the approach does not focus on individual tree failure (Gardiner et al. 2008).

Mayer (1987) cautioned that no tree can survive violent storms and posed the question of how the results from investigations on tree sways can be used in practice. How trees fail under dynamic wind loading is not known because the actual dynamic process has never been verified in field experiments due to lack of measurements (Hale et al. 2010). The assumption that the extreme (maximum) wind loading in any particular storm is the key factor in determining whether damage occurs has never been verified in field experiments and it is possible that root fatigue (Rodgers et al. 1995) from a number of storms could actually be more important (Hale et al. 2010).

Studies of the impact of hurricane force winds on urban trees in Florida, U.S., found failure by trunk breakage exceeded overturning in some species [*Pinus elliottii* (slash pine), 64% broke during Hurricane Jeanne], but other species [*Pinus clausa* (sand pine)] had 71% breakage during Hurricane Jeanne (Duryea et al. 2007). Following another hurricane (Ivan), uprooting was the main mechanism of failure. Other than post-storm surveys that relate estimated wind speed to tree failures (Kane 2008), there are at present no definitive methods that predict tree failure at a specific wind speed.

Dynamic Analysis Methods

The principles of the dynamic behavior of structures was first published by Den Hartog (1956), and most subsequent texts (e.g., Clough and Penzien 1993; Chopra 1995; Balachandran and Magrab 2004) still use the fundamental equations described in this book. Dynamic analysis examines the forces and displacements of moving structures and considers the inertial forces of mass (m), the elastic forces (k) as in a spring, and the damping forces (c) that dissipate energy. A static analysis considers only the spring forces (k).

When studying the dynamic behavior of a structure, three different approaches are commonly used (Clough and Penzien 1993):

1. lumped-mass procedure, mass concentrated at a discrete point
2. generalized displacements for uniformly distributed mass, where a trunk is treated as a beam
3. the finite element method (FEM)

The Lumped-mass Procedure

The lumped-mass procedure assumes the mass is concentrated at a discrete point as it oscillates dynamically. This greatly simplifies the analysis because inertial forces develop only at these mass points. This method has been used to develop spring-mass-damper models for trees as a single mass (e.g. Milne 1991; Miller 2005), as seen in Figure 1, or as a complex system of coupled masses that

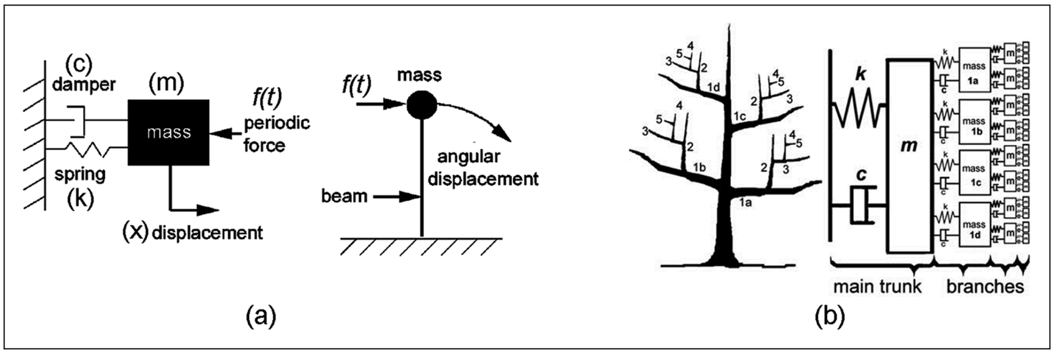

Figure 1. Dynamic models using a spring-mass-damper system representing: (a) a tree as a single mass (Miller 2005), and (b) as multiple masses with a trunk and branches (James et al. 2006).

represent the trunk and branches (James et al. 2006; Theckes et al. 2011; Murphy and Rudnicki 2012).

A simple spring-mass-damper system (Figure 1a) is described by a second-order differential equation:

$$m\ddot{x} + c\dot{x} + kx = f(t) \quad [1]$$

where c, m, and k are damping coefficient, mass, and stiffness, respectively; x, ẋ, and ẍ are the displacement, velocity, and acceleration, respectively; and *f*(t) is the wind-induced time varying (dynamic) force. Equation 1 describes the motion of a single degree of freedom system (SDOF), and if used for analysis of a tree (Figure 1a), approximates the tree to a single oscillating mass (m) with a stiffness (k) and a damping (c) (Miller 2005). A more complex mass model representing branches as oscillating masses attached to a main trunk (Figure 1b) extends this concept to consider branches as oscillating masses attached to the main trunk (James et al 2006).

The oscillating lumped-mass model has been used for trees (Milne 1991; Baker and Bell 1992; Peltola and Kellomaki 1993; Guitard and Castera 1995; Peltola 1996a; Baker 1997; Kerzenmacher and Gardiner 1998; Saunderson et al. 1999; Flesch and Wilson 1999b; England et al. 2000; Miller 2005; James et al. 2006; Jonsson et al. 2007; James 2010; Thekes et al. 2011; Murphy and Rudnicki 2012). Analyses of the mass-spring-damper model of a tree may include a spectral analysis approach using Fourier transformations and transfer functions based on a SDOF model that is often not explicitly stated (Peltola 1996b; Rudnicki et al. 2008; Schindler 2008).

A simple model of a tree (Figure 1a) has a dynamic response whose response amplitude is frequency dependent. Depending on the frequency of sway, the dynamic response is dominated by stiffness, damping, or inertia (Balachandran and Magrab 2004). At low frequencies, the response is dominated by stiffness. As the frequency of the applied force increases, the dynamic response increases until it equals the natural frequency of the system. At this point resonance occurs and there is an amplification of the sway, which depends on the damping, and is known as the damping-dominated region. As frequencies increase further, the rapid force impulses do not cause the mass to move because of its inertia; this is known as the inertial region.

In the damping-dominated region, at frequencies close to the natural frequency, the amplification of sway response has been described for trees as a DAF (Sellier and Fourcaud 2009; Ciftci et al. 2013) (James 2010).

The DAF applied to trees by Sellier and Fourcaud (2009) was defined as the ratio of the maximum displacement under turbulent wind to the displacement caused by the static, instantaneous wind force. DAF was calculated at breast height and at the base of the live crown of a 35-year-old maritime pine (*Pinus pinaster* Ait.), with values between 0.98 and 1.19. These values seem low due to the DAF being based on displacements, which at breast height would always be small. Ciftci (2012) used FEM to investigate the effect of branches on DAF of a large sugar maple (*Acer saccharum* L.), also finding that changes to tree geometry induced greater changes in DAF. However, recent studies have indicated that different growth forms in woody plants show distinct ontogenetic trends in mechanical properties (Dahle and Grabosky 2010b; Speck and Burgert 2011), so material properties cannot be ignored in dynamic analyses (Moore and Maguire 2008; Ciftci 2012).

The DRF (James 2010) was defined as the ratio of maximum base moment to mean base moment. It varied among species; more flexible trees (*Cupressus sempervirens* L., *Wash-*

ingtonia robusta H. Wendl.) exhibited higher values than stiffer trees (*Agathis australis* D. Don).

Damping has the effect of reducing the amplitude of oscillation and is most effective around the natural frequency region. Damping has little effect at lower frequencies, shown as the static region, and also has little effect at the higher frequencies where the inertia of the mass is the dominant effect on the response. Damping is usually not well understood in vibrating structures (Clough and Penzien 1993) and may be more complex in nature as it may have a non-linear response to produce soft and hard spring mass systems (Miller 2005). In trees, damping forces are considered velocity dependent (Kollmann and Krech 1960; Moore and Maguire 2004; Jonsson et al. 2007) and include frictional forces, aerodynamic drag, collisions, and internal (viscoelastic) forces (Milne 1991).

Because the amplitude response of a dynamic structure is frequency dependent, the natural frequencies of trees have been investigated by either (a) inducing sway in still air conditions, usually with an attached rope (Sugden 1962; Mayhead 1973a; Mayhead et al. 1975; Milne 1991; Gardiner 1992; Roodbaraky et al. 1994; Guitard and Castera 1995; Baker 1997; Flesch and Wilson 1999; Moore and Maguire 2004; Jonsson et al. 2007; Kane and James 2011) or (b) by measuring the tree response in wind conditions and using a power spectrum approach (Holbo et al. 1980; Peltola et al. 1993; Gardiner 1995; Hassinen et al. 1998; James et al. 2006; Moore 2008; Rudnicki et al. 2008).

Complex mass models of trees (e.g., Figure 1b) produce more complex dynamic responses known as multimodal responses, which are discussed later in this review, and also develop mass damping when two or more coupled masses oscillate.

Dynamics of Beams with Distributed Mass

Another method of dynamic analysis considers the structure of a beam or column with the mass distributed along its length. The dynamic equation for a uniform vibrating beam is a fourth-order partial differential equation that is accurate for small deflections, and has been used to study the oscillations and damping of the stems of woody and non-woody plants (Finnigan and Mulhearn 1978; Mayer 1987; Spatz and Speck 2002; Brüchert et al. 2003; Speck and Spatz 2004). Using this equation for tree analysis assumes the tree is like a beam with mass distributed along its length. The first structural model of a tree (Greenhill's model, Spatz 2000) considered the tree as a pole (Figure 2), and used a static analysis to calculate how tall a tree could grow before it buckled under its own weight (Spatz 2000). There was no consideration of dynamic loads from winds.

Greenhill's (1881) simple pole model for trees has been the conceptual basis for both static and dynamic analyses and has been used to analyze dynamics of trees growing in closely spaced plantations or forests (Papesch 1974; Finnigan and Mulhearn 1978; Mayer, 1987; Wood 1995; Peltola 1996b;

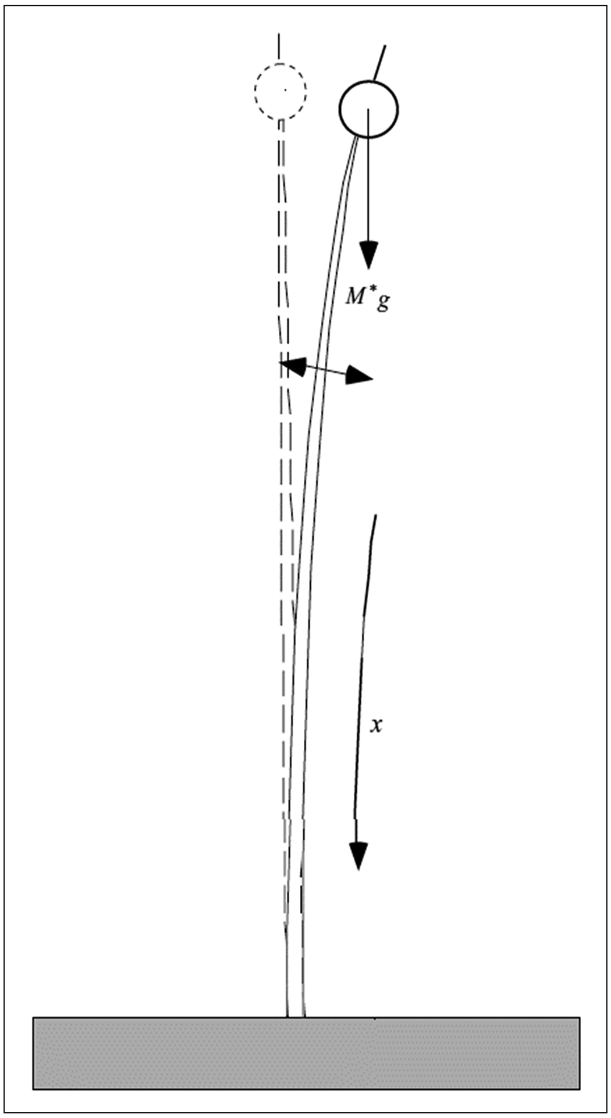

Figure 2. Plant stems considered as a beam with distributed mass (Brüchert et al. 2003).

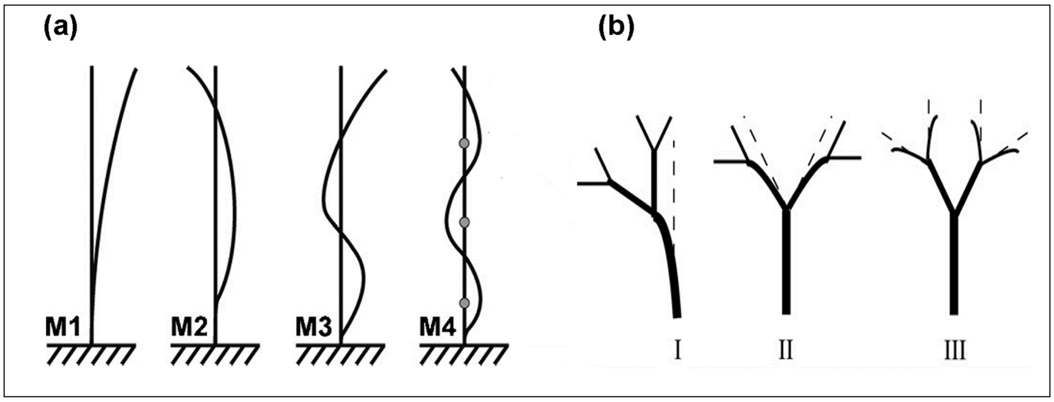

Figure 3. Dynamic modes applied to trees: (a) modes of a beam (Schindler et al. 2010) and (b) modes of branched structures (Rodriguez et al. 2008).

Flesch and Wilson 1999; Gardiner et al. 2000; Spatz 2000; Novak et al. 2001; Spatz and Speck 2002; Bruchert et al. 2003; Gardiner et al. 2005; Jonsson et al. 2007; Spatz et al. 2007; Moore and Maguire 2008; Rudnicki et al. 2008; Schindler 2008).

The dynamic response of an oscillating beam is more complex than for a single mass because the beam can vibrate in many modes. The first mode is a simple back and forth sway of the whole beam at a frequency known as the natural or fundamental frequency. Other sway responses are possible and the beam may deflect in different shapes (known as mode shapes) that occur at different frequencies (Figure 3a). In theory, a beam considered a uniform continuous structure has an infinite number of vibrating modes, but in practice, most of the energy of vibration occurs in the first few modes. The first or fundamental mode occurs at the lowest frequency, and has the most energy and amplitude.

Finite Element Method

In dynamic analysis, FEM combines features of both the lumped mass and uniformly distributed mass procedures. It is applicable to all structures and requires computer analysis due to the complex calculations (Sellier et al. 2006, Dupuy et al. 2007; Rodriguez et al. 2008; Moore and Maguire 2008; Sellier and Fourcaud 2009; Theckes et al. 2011; Ciftci 2012; Ciftci et al. 2013).

FEM divides a structure or beam into an appropriate number of elements whose sizes may vary, and the ends of each element (nodes) become the generalized coordinates. The deflection of the complete structure can then be expressed in terms of generalized coordinates. This method is good for one- and three-dimensional structures and has the advantage of being able to select the desired number of generalized coordinates by dividing the structure into the appropriate number of segments. For uniform materials, such as steel and concrete, interpolation functions of each segment may be identical and computations are simplified (Figure 4).

An advantage of FEM is that complex wind-loading scenarios can be modeled. The dynamic response of the structure (i.e., the tree) is important, but an equally important factor is the wind loading, which can be quite complex (Finnigan and Brunet 1995; Belcher et al. 2012). Recent FEM studies have investigated tree response to different wind-loading scenarios (Sellier et al. 2008; Sellier and Fourcaud 2009). Use of FEM to explore the complex structural dynamics of decurrent trees holds great promise, but it requires accurate empirical measurements of many parameters peculiar to the tree and loading conditions to produce a reliable result.

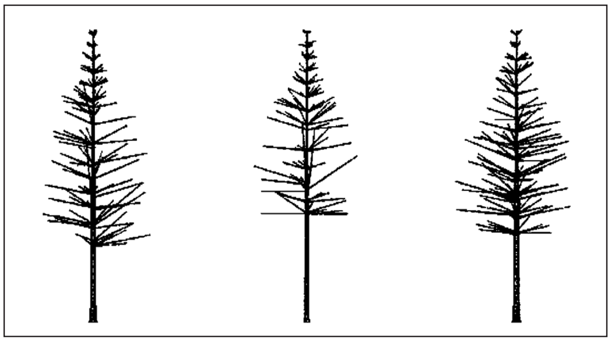

Figure 4. Finite element models showing the crown structure of three trees (Moore and Maguire 2008).

STRATEGIES USED IN DYNAMICS RESEARCH ON TREES

Different strategies have been used by various researchers to study tree biomechanics, and tree dynamics in winds. In this review the strategies are broadly grouped as:

1. Forestry – (trees in groups) economic damage on plantation grown trees,
2. Open-grown trees – (individual trees with branches, both excurrent and decurrent) tree stability and risk assessment, predominantly in urban areas,
3. Wind tunnels – small trees to measure drag coefficients in constant velocity winds, and
4. Modeling – (dynamic models of trees) computer studies, finite element methods and mathematical modeling.

Forestry

Forestry studies examine plantation trees (mainly conifers) and the economic losses caused by damaging winds (Moore and Maguire 2005; Peltola 2006), usually with the aim to determine threshold values of storm damage. Threshold values include wind speed, gustiness, duration of storm, terrain, soil type, soil moisture, stand characteristics (e.g., height, density, diameter at breast height, crown length), and the physical condition of a tree (Mayer 1987). The threshold value of wind speed at which damage to trees occurs, termed the critical wind speed, is an important variable for forest managers (Peltola 2006) and in forest modeling (Gardiner 1995; Moore and Maguire 2004; Frank and Ruck 2008). The factors of site, tree species, soil, wind climate, critical wind speed, and silvicultural treatments, such as thinning, are considered together in order to calculate the risk of damage to a naturally regenerated forest or plantation. The forestry studies estimate the percent damage to a group average of trees, rather than explicitly predicting failure of any individual tree.

To predict the percentage of trees in a forest stand likely to fail during a storm, mechanistic models have been developed (Gardiner et al. 2008; Frank and Ruck 2008; Schelhaas 2008; Wood et al. 2008). The models calculate the critical wind speed required to break or overturn trees, and then determine the probability of damage at the geographic location of the trees, based on some assessment of local wind climatology and empirical relationships. Models have been shown to be valid in certain circumstances (Gardiner et al. 2000), but their deterministic nature is sometimes at odds with field observations of wind throw. By definition, the models are restricted to excurrent trees in plantations and are really an application of statics to a dynamic phenomenon, and so are not yet applicable to open-grown trees in urban areas.

There has been considerable work using static pulling tests, mainly on forest conifers (Nicoll et al. 2006) and on small and young trees (Lundström et al. 2007) with a high slenderness ratio usually above 50 and often over 100 (e.g., slenderness values [46-136] Hale et al. 2010; [58-94] Jonsson et al. 2006). Tree-pulling tests have had an important role in providing valuable information on mechanical stability of trees of varying size and tree species, and the information is useful in mechanistic modeling, but the simulation of static loading by tree pulling alone is not enough to explain the mechanical stability of trees (Peltola 2006).

The critical wind speeds that cause failure depend on tree species, growth pattern, and location, and estimates vary. However, ultimately few tree species can survive violent storms with mean wind speeds over a period of 10 minutes, exceeding 30 m s^{-1} near the top of the canopy without damage (Peltola 1996a).

Open-grown Trees

The distinction between open-grown trees and forest trees is made in this review because of differences in the growth and form of the trees, particularly with respect to their canopy architecture. Research on dynamic response of forest trees may not be applicable to open-grown trees that develop a complex distribution of branch masses. When applying dynamic methods to tree sway in winds, recent research has indicated that the branches and the form of the tree are important in understanding how trees respond in winds (James et al. 2006; Spatz et al. 2007; Rodriguez et al. 2008; Sellier and Fourcaud 2009; Theckes et al. 2011; Ciftci et al. 2013).

Research on open-grown trees in winds aims to understand how individual trees respond in winds, and investigates aerodynamic properties (Baker and Bell 1992; Roodbaraky et al. 1994; Baker 1997; Ennos 1999), dynamic properties of frequency and drag (Kane and Smiley 2006; Kane and James 2011), effect of pruning dose on wind response (Gilman et al. 2008a; Gilman et al. 2008b; Pavlis et al. 2008), and wind loads (James 2006; James 2010).

There is very little data on the wind loading of open-grown trees during storms, and much of what we know about how trees fail comes from post-storm tree damage surveys (Duryea et al. 2007; Lopes et al. 2007; Kane 2008; Matheny and Clark 2009). Extreme European wind storms on December 26–28, 1999, were directly responsible for killing 95 people in France; 15 in Germany; 11 in Switzerland; 11 in the United Kingdom; and 5 in Spain. Damage was estimated at more than USD $10 billion where wind speeds exceeding 160 km/h were recorded along the French coast (Lopes et al. 2007).

There is currently no definitive method to predict failure of an individual tree. Arboricultural assessments of trees include visual tree assessment (Mattheck and Breloer 1994), tree risk assessment methodology (Smiley et al. 2011), quantified tree risk assessment (Ellison 2005), and statics integrated methods that combine static pulling with dynamic wind load assessment (Wessolly 1991; Brudi and van Wassenaer 2002; Detter and Rust 2013). The effect of pruning dose and trunk movement in tropical storm winds has been investigated (Gilman et al. 2008a), using artificially generated winds at speeds up to 26.8 ms^{-1} on trees of 6.1 m average height. Trees generally moved similarly in wind regardless of ANSI pruning type applied, although crown/branch thinning may be more effective in reducing motion than other pruning types. Gilman et al. (2008a) suggested that it may not be wise to extrapolate these results to larger trees, and that further testing is required to examine the pruning effect of individual branches when they are coupled as a continuous dynamic structure. Conflicting results were obtained in further studies using similar trees and methods, where crown thinning was less effective at reducing trunk movement (Gilman et al. 2008b). In this study it was noted that branches on thinned trees appeared to move more than branches on other treatments but not in the same direction. This complex branch movement indicates that the dynamic effects of branches may play an important role in acting as a buffer to dampen and reduce motion (Moore and Maguire 2005; James et al. 2006).

Wind Tunnels

Wind tunnel tests have been used to study wind effects on trees, but there are serious limitations due to the size of the wind tunnel and the trees that can fit into them. In general, derived results are only strictly applicable under similar conditions, but the forces are of the right magnitude for mechanistic models, similar to static pulling experiments (Peltola 2006). Scale models of trees have been used in wind tunnels to represent forest trees, to study the dynamics of wind turbulence on forest canopies and to examine the effects of commercial practices such as thinning and spacing (Stacey et al. 1994; Gardiner and Stacey 1996; Gardiner et al. 1997; Gilman et al. 2008a).

By necessity, trees in wind tunnels are small and the wind flow conditions are steady state or quasi-static (Holmes 2007) and drag dominated. Because conditions in wind tunnels are quasi-static, tests on trees have previously been reported in static papers on trees (Peltola 2006) rather than in dynamic reviews. One of the problems with results from wind tunnel tests is the question of scale, and how to select the appropriate wind speed in relation to the scale of the model and of full-sized trees (Peltola 2006).

Wind tunnel tests on trees have been performed on individual scale models (Tevar Sanz et al. 2003; Gromke and Ruck 2008), on model canopies (Finnigan and Mulhearn 1978; Wood 1995; Gardiner et al. 1997; Novak et al. 2001; Gardiner et al. 2005), and on small trees (Fraser 1967; Mayhead 1973b; Rudnicki et al. 2004; Vollsinger et al. 2005; Cao et al. 2012) and individual leaves (Vogel 1989). Some studies conducted in wind tunnels have investigated the effect of pruning on drag of conifers (Fraser 1967; Mayhead et al. 1975; Rudnicki et al. 2004) and deciduous trees (Vollsinger et al. 2005), but interpretation of results is limited because few replications were used (Fraser 1967; Mayhead et al. 1975) and the trees were small (less than 2 m tall) (Rudnicki et al. 2004; Vollsinger et al. 2005). Smiley and Kane (2006) and Pavlis et al. (2008) simulated wind tunnel conditions by placing small trees on the back of a truck and driving at high speed. They examined the effect of pruning on drag reduction by applying different pruning methods. Reduction in drag induced bending moment differed by pruning type, mainly due to the mass of foliage removed, but predicting the reduction in drag was not reliable based on area of crown removed. Tree mass was the best predictor of drag for red maple (*Acer rubrum*), but these results were on small trees, and the authors recommended caution when extrapolating drag values to larger red maples.

A frequently cited study of drag on British forest trees (Mayhead 1973b) used a wind tunnel to determine drag coefficients, but Mayhead commented that it is probably unsound to test trees less than 3–4.5 m high because larger trees have a different morphology (Niklas 1994a; Niklas 1995; Osunkoya et al. 2007; Dahle and Grabosky 2010a). Mayhead (1973b) found large variations in results both between and within species and suggested that the range of variation was either natural or a result of poor technique.

Wind tunnels are used by civil engineers to determine drag on solid objects known as bluff bodies (Holmes 2007), and constant wind velocity is used to create steady state or quasi-static conditions. Bluff bodies have a fixed frontal area exposed to the wind, a fixed shape that has a set value of streamlining, and a constant drag coefficient that is proportional to the square of velocity. Results from small bluff body models may be scaled up for large structures such, as tall buildings, where additional factors, such as the aerodynamic admittance function, may need to be considered (Holmes 2007). These methods may not be suitable for flexible objects, such as trees, because the response of small-scale models under constant wind speed conditions may not represent the response of large trees under actual wind conditions (Mayhead 1973b). The drag coefficient for trees may not be a constant value and could be proportional to wind speed (v) or the square of wind speed (v^2) (Cullen 2002b). Average values of drag for trees are often quoted, but the large range and variability is often overlooked. Mayhead (1973b) reported drag coefficients for several conifer species of importance to British forestry and the results have become standard values used in windthrow risk modeling, despite very small sample sizes (e.g., Gardiner et al. 2000). Gardiner et al. (2005) cautioned that these wind tunnel tests are a simplification of a real forest, and in some instances can only provide a rough approximation to reality.

COMPLEX TREE MODELS

All models used for dynamic analysis of trees make assumptions, but some assumptions (e.g., ignoring branches or treating them as rigid, lumped masses) may not adequately represent the complex dynamic response of trees (Moore and Maguire 2004). More complex models are needed to account for different tree shapes and species, and in particular account for the dynamic influence of branches (Kerzenmacher and Gardiner 1998; England et al. 2000; Sellier and Fourcaud 2009; Theckes et al. 2011; Ciftci 2012; Ciftci et al. 2013). The dynamic effect of branches on frequency and damping became increasingly important as crown architecture deviated from a slender, cantilevered beam (Sellier and Fourcaud 2009).

Models of trees must account for the dynamic contribution of branches, particularly in trees where the mass of branches is significant. For complex botanical structures, such as trees, a multi-degree of freedom system or a multimodal analysis is required to account for complex dynamic interaction of the branches and trunk (de Langre 2008; Rodriguez et al. 2008). The dynamics of trees with many large branches is complex because the swaying branches are attached to other swaying branches and then to the trunk. Each of the swaying masses influences the other swaying masses to create different modes of sway and also has an effect on the frequencies and damping of the overall structure. How the branched architecture and tree geometry influences the dynamics of the tree is therefore a central question to be investigated (Rodriguez et al. 2008). Multimodal analysis has only been used in a few studies to analyze the dynamic characteristics of trees (Fournier et al. 1993; Moore and Maguire 2005; Sellier et al. 2006; de Langre 2008; Rodriguez et al. 2008; Ciftci 2012; Murphy and Rudnicki 2012).

Multimodal response can occur in two different ways: (a) in beams (Figure 3a) and (b) in branched structures (Figure 3b). Multimodal response in beams occurs where the distributed mass along a single beam flexes in a number of modal shapes (Figure 3a) and is described previously in the section on beams. Although it is a multimodal dynamic analysis, the beam model does not account for oscillating branches.

Multimodal response in branched structures (Figure 3b) occurs when several coupled masses (branches) oscillate in a complex manner, often with an in-phase and out-of-phase response so that several modal sway responses are possible. The coupled masses, with their individual oscillation response, are connected to another oscillating mass, resulting in a coupled response of the combined masses. The branched multimodal method has been applied to trees where the branches are considered as coupled masses that oscillate on the trunk, which itself is an oscillating mass (James et al. 2006; Spatz, 2007; Rodriguez et al. 2008; Thekes et al. 2011; Ciftci 2012; Murphy and Rudnicki 2012; Ciftci et al.

2013). It is possible to extend this branched concept to second- and third-order branches where the complexity could be expected to increase further.

Complex models of trees that represent the dynamic oscillations of branches have used either (a) a multiple spring-mass-damper model (James 2003; James et al. 2006; Spatz 2007; Thekes et al. 2011; Murphy and Rudnicki 2012) or (b) a FEM approach (Rodriguez et al. 2008; Ciftci 2012; Ciftci et al. 2013) where modes are generated from branches moving together or apart in a complex manner (as in a fractal tree) (Rodriguez et al. 2008).

Where multimodal response occurs due to the swaying branches oscillating with each other, a damping effect known as mass damping may occur. A mass damping system described by Den Hartog (1956) has been defined for trees (James et al. 2006), and occurs when the branches sway together (in phase) or against each other (out of phase) in a complex manner. Damping from branches has been identified for a two degree-of-freedom system in a T- or Y-shaped branched structure (Spatz et al. 2007; de Langre 2008; James 2010; Thekes et al. 2011; Murphy and Rudnicki 2012; Spatz and Thekes 2013) based on a tuned mass damper system and in trees creates a modal energy transfer (de Langre 2008; Thekes et al. 2011; Spatz and Thekes 2013) as a protective mechanism against large sways. Complex dynamics that include branches could be beneficial to the tree by enhancing wind energy dissipation through a mechanism called multiple resonance damping (Spatz et al. 2007), multiple mass damping (James et al. 2006), or branch damping (Spatz and Thekes 2013). A prerequisite for this mechanism to occur is a multimodal behavior of the tree, with high modal density in the frequency range and significant branch deformations.

This dynamic response was found for trees with contrasting architectures in a three-dimensional modal analysis and FEM modeling (Rodriguez et al. 2008). Branch oscillations influence the dynamic behavior of trees to a greater extent than can be explained simply by their additional mass (Moore and Maguire 2008; Ciftci 2012).

TREE MORPHOLOGY AND MATERIAL PROPERTIES

Size and morphology of trees need to be considered when using complex dynamic analyses because the dynamics of branches affects the oscillating frequency and damping of the whole tree (Rodriguez et al. 2008; Speck and Burgert 2011). In a study of tree aerodynamic behavior it was found that material properties play only a limited role in tree dynamics (Sellier and Fourcaud 2009). In contrast, small morphological variations can produce extreme behaviors, such as either very little or nearly critical dissipation of stem oscillations. Effects of branch geometry on dynamic amplification are substantial yet not linear (Sellier and Fourcaud 2009). Recent studies in the biomechanics of plant stems indicate that different growth forms in woody plants show distinct ontogenetic trends in mechanical properties (Dahle and Grabosky 2010b; Speck and Burgert 2011).

Open-grown trees have diverse branch morphology, as shown in a survey of 40 woody tree and shrub species in New York (Evans et al. 2008). The size of a tree is also an important parameter because large trees have a different morphology to small trees, and it is probably unsound to test trees less than 3–4.5 m tall (Mayhead 1973b). The morphology of branches also changes with size (Bertram 1989; Dahle and Grabosky 2010a), which must be taken into account. Natural morphological variation within and across species of open-grown trees need to be considered, and care taken when attempting to scale up results and extrapolate data. (Mayhead 1973b; Gilman et al. 2008a)

Dynamics studies of olive trees (Castro-Garcia et al. 2008) and walnut trees (Rodriguez et al. 2012) swaying under forced vibration during harvesting also show the multimodal response, similar to the wind excitation results, which is due to the dynamic interaction of branches on the tree.

CONCLUDING REMARKS

The dynamic response of open-grown trees in winds is greatly influenced by the size and form of the tree, and at least partly due to the dynamics of branches. Simple models have been used for forest and plantation trees and are useful for dynamic analysis of slender trees with few branches. However, more complexity, such as through a multimodal approach, is needed for a dynamic analysis of open-grown trees, because the dynamic coupling of branches has an influence on the response of the tree (de Langre 2008; Rodriguez et al. 2008).

There appear to be gaps in the literature on several topics relating to dynamic analysis of open-grown trees and their response in winds, including:

1. Recommendations for pruning open-grown trees to reduce wind damage (Gilman et al. 2008b).
2. The dynamic contribution and the damping effects of branches. Studies indicating that the form of the tree has a greater influence than the material properties (Sellier and Fourcaud 2009) have implications for branch removal and future pruning practices.
3. Modeling of open-grown trees should account for the multimodal branch response. The complexity of dynamic analysis is likely to increase in the near future but will need to be condensed into simpler methods for practical use.
4. Tree failure under actual wind conditions has not yet been measured (Hale et al. 2010), and so extending the results from current research is difficult, especially when trying to determine tree failure and stability in winds.
5. Associated with tree failure is the understanding of the energy transfer from the wind to the tree. There is little published data on actual wind loads on trees and understanding the energy transfer process may assist in understanding how trees and branches dissipate energy and dampen the wind energy. This may be an important factor in understanding how trees survive otherwise damaging winds.
6. Finally, the topic of torsional forces and loads on trunks and branches has not yet been investigated, yet may be critical in understanding the total loads on trees (Niklas 1992). Torsional forces that twist trunks and branches are observed in trees during winds, but no method has yet been developed to measure the dynamic torsional loads experienced by trees during winds.

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LITERATURE CITED

Baker, C.J. 1997. Measurements of the natural frequencies of trees. Journal of Experimental Botany 48:1125–1132.

Baker, C.J., and H.J. Bell. 1992. Aerodynamics of urban trees. Journal of Wind Engineering and Industrial Aerodynamics 44:2655–2666.

Balachandran, B., and E.B. Magrab. 2004. Vibrations. Thomson Pub.

Belcher, S.E., I.N. Harman, and J.J. Finnigan. 2012. The wind in the willows: Flows in forest canopies in complex terrain. Annual Review of Fluid Mechanics 44:479–504.

Bertram, J.E.A. 1989. Size-dependent differential scaling in branches: The mechanical design of trees revisited. Trees 4:241–253.

Blackburn, P., J.A. Petty, and K.F. Miller. 1988. An assessment of the static and dynamic factors involved in windthrow. Forestry 61(1):29–43.

Brüchert, F., F. Becker, and T. Speck. 2000. The mechanics of Norway spruce [*Picea abies* (L.) Karst]: Mechanical properties of standing trees from different thinning regimes. Forest Ecology and Management 135:45–62.

Brüchert, F., O. Speck, and H.-C.H. Spatz. 2003. Oscillations of plants' stems and their damping: Theory and experimentation. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 358(1437):1487–1492.

Brudi, E., and P. Van Wassenaer. 2002. Trees and statics: Nondestructive failure analysis. pp. 53–69. In: E.T. Smiley and K. Coder (Eds.). Tree Structure and Mechanics Conference Proceedings: How Trees Stand Up and Fall Down. ISA, Champaign, Illinois, U.S.

Cao, J., Y. Tamura, and A. Yoshida. 2012. Wind tunnel study on aerodynamic characteristics of shrubby specimens of three tree species. Urban Forestry & Urban Greening 11(4):465–476.

Castro-Garcia, S., G.L. Blanco-Roldan, J.A. Gil-Ribes, and J. Aguera-Vega. 2008. Dynamic analysis of olive trees in intensive orchards under forced vibration. Trees 22:795–802.

Chopra, A.K. 1995. Dynamics of structures. Prentice Hall, New Jersey, U.S.

Ciftci, C. 2012. Risk quantification of maple trees subjected to wind loading. Doctoral dissertation. University of Massachusetts, Amherst Massachusetts.

Ciftci, C., S.F. Brena, B. Kane, and S.R. Arwade. 2013. The effect of crown architecture on dynamic amplification factor of an open-grown sugar maple (*Acer saccharum* L.). Trees, Springer, March.

Clough, R.W., and J. Penzien. 1993. Dynamics of structures. McGraw Hill, New York, City, New York, U.S.

Coutts, M.P. 1986. Components of tree stability in Sitka spruce on peaty gley soil. Forestry 59:173–197.

Coutts, M.P., and J. Grace. 1995. Wind and Trees. Cambridge University Press.

Cullen, S. 2002a. Trees and wind: A bibliography for tree care professionals. Journal of Arboriculture 28(1):41–51.

Cullen, S. 2002b. Trees and Wind; Wind scales and speeds. Journal of Arboriculture 28(5):237–242.

Dahle, G.A., and J.C. Grabosky. 2010a. Allometric patterns in *Acer platanoides* (Aceraceae) branches. Trees: Structure and Function 24:321–326.

Dahle, G.A., and J.C. Grabosky. 2010b. Variation in modulus of elasticity (E) along *Acer platanoides* L. (Aceraceae) branches. Urban Forestry & Urban Greening 9:227–233.

Dahle, G.A., K.R. James, B. Kane, .J. Grabosky, and A. Detter. 2013. Tree Biomechanics Literature Review. Arboriculture & Urban Forestry (*in review*)

de Langre, E. 2008. Effects of wind on plants. Annual Review of Fluid Mechanics 40:141–168.

de Langre, E. 2012. Methodological advances in predicting flow-induced dynamics of plants using mechanical-engineering theory. Journal of Experimental Biology 215:914–921.

Den Hartog, J.P. 1956. Mechanical Vibrations. McGraw-Hill, New York City, New York, U.S.

Detter, A., and S. Rust. 2013. Aktuelle Untersuchungsergebnisse zu Zugversuchen [Latest results in research on pulling tests] In: D. Dujesiefken (Ed.). Jahrbuch der Baumpflege 2013 (*in press*).

Dupuy, L., T. Fourcaud, P. Lac, and A. Stokes. 2007. A generic 3D finite element model of tree anchorage integrating soil mechanics and real root system architecture. American Journal of Botany 94(9):1506–1514.

Duryea, M.L., E. Kampf, R.C. Littel, and C.D. Rodriguez-Pedraza. 2007. Hurricanes and the urban forest II: Effects on tropical and subtropical tree species. Arboriculture & Urban Forestry 33:98–112.

Ellison, M.J. 2005. Quantified tree risk assessment used in the management of amenity trees. Journal of Arboriculture 31(2):57–65.

England, A.H., C.J. Baker, and S.E.T. Saunderson. 2000. A dynamic analysis of windthrow of trees. Forestry 73(3):225–237.

Ennos, A.R. 1999. The aerodynamics and hydrodynamics of plants. Journal of Experimental Biology 202:3281–3284.

Evans, L.S., Z. Kahn-Jetter, J. Torres, and M.T.P. Martinez. 2008. Mechanical stresses of primary branches: A survey of 40 woody tree and shrub species. Trees 22:283–289.

Finnigan J.J., and Y. Brunet. 1995. Turbulent airflow in forests on flat and hilly terrain. In: M.P. Coutts and J. Grace (Eds.). Wind and Trees. Cambridge University Press.

Finnigan, J.J., and P.J Mulhearn. 1978. Modeling waving crops in a wind tunnel. Boundary-Layer Meteorology 14:253–277.

Flesch, T.K., and J.D. Wilson. 1999. Wind and remnant tree sway in forest cutblocks. II. Relating measured tree sway to wind statistics. Agricultural and Forest Meteorology 93:243–258.

Fournier, M., P. Rogier, E. Costes, and M. Jaeger. 1993. Modélisation mécanique des vibrations propres d'un arbre soumis aux vents, en fonction de sa morphologie. Annales des Sciences Forestieres 50:401–412.

Frank, C., and B. Ruck. 2008. Numerical study of the airflow over forest clearings. Forestry 81(3):259–277.

Fraser, A.I., and J.B.H. Gardiner. 1967. Rooting and stability in Sitka spruce. Forestry Commission Bulletin. No. 40. HMSO, London.

Gardiner, B., and G. Stacey. 1996. Designing forest edges to improve wind stability. Forestry Commission Technical Paper 16. Forestry Commission, Edinburgh, UK.

Gardiner, B., B. Marshall, A. Achim, R. Belcher, and C. Wood. 2005. The stability of different silvicultural systems: A wind-tunnel investigation. Forestry 78:471–483.

Gardiner, B., H. Peltola, and S. Kellomaki. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. Ecological modeling 129:1–23.

Gardiner, B., K.E. Byrne, S. Hale, K. Kamimura, S.J. Mitchell, H. Peltola, and J.-C. Ruel. 2008. A review of mechanistic modeling of wind damage risk to forests. Forestry 81(3):447–463.

Gardiner, B.A. 1992. Mathematical Modelling of the static and dynamic characteristics of plantation trees. pp. 40–61. In: J. Franke and A.E. Roeder (Eds.). Mathematical Modelling of Forest Ecosystems. Saunders Verlag, Frankfurt.

Gardiner, B.A. 1995. The interactions of wind and tree movement in forest canopies. pp. 41–59. In: M.P. Coutts and J. Grace (Eds.). Wind and Trees. Cambridge University Press.

Gardiner, B.A., and C.P. Quine. 2000. The mechanical adaption of tree to environmental influences. pp. 71–82. Proceedings of 3rd Plant Biomechanics Conference, Freiberg.

Gardiner, B.A., G.R. Stacey, R.E. Belcher, and C.J. Wood. 1997. Field and wind tunnel assessments of the implications of re-spacing and thinning for tree stability. Forestry 70(3):233–252.

Gilman, E.F., J.C. Grabosky, S. Jones, and C. Harchick. 2008a. Effects of Pruning Dose and Type on Trunk Movement in Tropical Storm Winds. Arboriculture & Urban Forestry 34(1):13–19.

Gilman, E.F., F. Masters, and J.C. Grabosky. 2008b. Pruning Affects Tree Movement in Hurricane Force Wind. Arboriculture & Urban Forestry 34(1):20–28.

Gromke, C., and B. Ruck. 2008. Aerodynamic modeling of trees for small-scale wind tunnel studies. Forestry 81(3):243–258

Guitard, D.G.E., and P. Castera. 1995. Experimental analysis and mechanical modelling of wind-induced tree sways. pp. 182–194. In: M.P. Coutts and J. Grace (Eds.). Wind and Trees. Cambridge University Press: Cambridge, UK.

Hale, S., B. Gardiner, A. Wellpott, B. Nicoll, and A. Achim. 2010. Wind loading of trees: Influence of tree size and competition. European Journal of Forest Research 131(1):203–217.

Hassinen, A., M. Lemettinen, H. Peltola, D. Kellomaki, and B.A. Gardiner. 1998. A prism-based system for monitoring the swaying of trees under wind loading. Agricultural and Forest Meteorology 90:187–194.

Hedden, R.L., T.S Fredericksen, and S.A. Williams. 1995. Modeling the effect of crown shedding and streamlining on the survival of loblolly pine exposed to acute wind. Canadian Journal of Forest Research 25(5):704–712.

Holbo, H.R., T.C. Colbett, and P.J. Horton. 1980. Aeromechanical behavior of selected Douglas-fir. Agricultural Meteorology 21:81–91.

Holmes, J.D. 2007. Wind Loading on Structures. 2nd edition. Taylor and Francis, New York City, New York, U.S. 380 pp.

James, K.R. 2003. Dynamic Loading of Trees. Journal of Arboriculture 29(3):165–171.

James, K.R. 2010. A Dynamic Structural Analysis Of Trees Subject To Wind Loading. Ph.D. thesis. University of Melbourne.

James, K.R., N. Haritos, and P.K. Ades. 2006. Mechanical stability of trees under dynamic loads. American Journal of Botany 93(10):1361–1369.

Jonsson, M.J., A. Foetzki, M. Kalberer, T. Lundstrom, W. Ammann, and V. Stockli. 2006. Root-soil rotation stiffness of Norway spruce [*Picea abies* (L.) Karst] growing on subalpine forested slopes. Journal of Plant and Soil 285:267–277.

Jonsson, M.J., A. Foetzki, M. Kalberer, T. Lundstrom, W. Ammann, and V. Stockli. 2007. Natural frequencies and damping ratios of Norway spruce [*Picea abies* (L.) Karst] growing on subalpine forested slopes. Trees 21:541–548.

Kane, B, and E.T. Smiley. 2006. Drag coefficients and crown area estimation of red maple. Canadian Journal of Forestry Research 36:1951–1958.

Kane, B. 2008. Tree failure following a wind storm in Brewster, Massachusetts, USA. Urban Forestry & Urban Greening 7:15–23.

Kane, B., and K.R. James. 2011. Dynamic properties of open-grown deciduous trees. Canadian Journal of Forestry 41(2):321–330.

Kane, B., M. Pavlis, J.R. Harris, and J.R. Seiler. 2008. Crown reconfiguration and trunk stress in deciduous trees. Canadian Journal of Forestry Research 38:1275–1289.

Kerzenmacher, T., and B.A. Gardiner. 1998. A mathematical model to describe the dynamic response of a spruce tree to the wind. Trees 12:385–394.

Kollmann, F., and H. Krech. 1960. Dynamische Messung der elastischen Holzeigenschaften und der Dämpfung [Dynamic measurement of damping capacity and elastic properties of wood]. Holz als Roh- und Werkstoff 18:41–54.

Lichtenegger, H., A. Reiterer, S.E. Stanzl-Tschegg, and P. Fratzl. 1999. Variation of cellulose microfibril angles in softwoods and hardwoods-a possible strategy of mechanical optimization. Journal of Structural Biology 128:257–269.

Lindström, H., J.W. Evans, and S.P. Verril. 1998. Influence of cambial age and growth condition on microfibril angle in young Norway spruce [*Picea abies* [L.] Karst.]. Holzforschung 52:573–581.

Lopes, A., S. Oliveira, M. Fragaso, J.A. Andrade, and P. Pedro. 2007. Wind risk assessment in urban environments: the case of falling trees during windstorm events in Lisbon. Conference on Bioclimatology and Natural Hazards, Slovakia.

Lundström, T., M. Stoffel, and V. Stöckli. 2008. Fresh-stem bending of silver fir and Norway spruce. Tree Physiology 28:355–366

Lundström, T., M.J. Jonsson, and M. Kalberer. 2007. The root-soil system of Norway spruce subject to turning moment; resistance as a function of rotation. Plant Soil 300:35–49.

Matheny, N., and J. Clark. 2009. Tree Risk Assessment. Arborist News 19(1):28–33.

Mattheck, C., and H. Breloer. 1994. The body language of trees. HMSO, Department of the Environment.

Mayer, H. 1987. Wind induced tree sways. Trees 1:195–206.

Mayhead, G.J. 1973a. Sway periods of forest trees. Scottish Forestry 27:19–23.

Mayhead, G.J. 1973b. Some drag coefficients for British trees derived from wind tunnel studies. Agricultural Meteorology 12:123–130.

Mayhead, G.J., B.H. Gardiner, and D.W. Durrant. 1975. A report on the physical properties of conifers in relation to plantation stability. Forest Commission Research and Development Division, Roslin, Midlothian, UK.

Miller, L.A. 2005. Structural dynamics and resonance in plants with nonlinear stiffness. Journal of Theoretical Biology 234:511–24.

Milne, R. 1991. Dynamics of swaying of *Picea sitchensis*. Tree-Physiology 9(3):383–399.

Mitchell, J. (Ed.). 2007. Proc. Int. Conf. Wind Trees. Vancouver: IUFRO.

Mitchell, J. (Ed.). 2008. Forestry 81(3).

Moore, J.R., and D.A. Maguire. 2004. Natural sway frequencies and damping ratios of trees: Concepts, review and synthesis of previous studies. Trees 18(2):195–203.

Moore, J.R., and D.A. Maguire. 2005. Natural sway frequencies and damping ratios of trees: Influence of crown structure. Trees 19:363–73.

Moore, J.R., and D.A. Maguire. 2008. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. Tree Physiology 28:75–83

Moulia, B., and M. Fournier (Eds.). 2012. Proceedings of the 7th Plant Biomechanics Conference, Aug 20-24, Clermont-Ferrand, France.

Murphy, K.D., and M. Rudnicki. 2012. A physics-based link model for tree vibrations. American Journal of Botany 99:1918–1929.

Nicoll, B.C., B. Gardiner, B. Rayner, and A.J. Peace. 2006. Anchorage of coniferous trees in relation to species, soil type, and rooting depth. Canadian Journal of Forest Research 36:1871–1883.

Niklas, K. J. 1992 . Plant biomechanics: An engineering approach to plant form and function. University of Chicago Press, Chicago, Illinois, U.S.

Niklas, K.J. 1994a. Allometry: The scaling of form and process. University of Chicago Press, Chicago, Illinois, U.S.

Niklas, K.J. 1995. Size-dependent allometry of tree height, diameter, and trunk-taper. Annals of Botany 75:217–227.

Novak, M.D., A.L. Orchansky, J.S. Warland, and R. Ketler. 2001. Wind tunnel modeling of partial cuts and cutblock edges for wind throw. pp. 176–192. In: S.J. Mitchell (Ed.). Windthrow assessment and management in British Columbia. Richmond, British Columbia, Canada.

Oliver, H.R., and G.J. Mayhead. 1974. Wind measurements in a pine forest during a destructive gale. Forestry 47:185–195.

Osunkoya, O.O., K. Omar-Ali. N. Amit, J. Dayan, D.S. Daud, and T.K. Sheng. 2007. Comparative height-crown allometry and mechanical design in 22 tree species of Kuala Belalong rainforest, Brunei, Borneo. American Journal of Botany 94:1951–1962.

Papesch, A.J.G. 1974. A simplified theoretical analysis of the factors that influence the wind throw of trees. pp. 235–242. In: A.J. Sutherland and D. Lindley (Eds.). Fifth Australasian Conference on Hydraulics and Fluid Mechanics, University of Canterbury, Christchurch, New Zealand

Pavlis, M., B. Kane, J.R. Harris, and J.R. Seiler. 2008. The effects of pruning on drag and bending moment of shade trees. Arboriculture & Urban Forestry 34:207–215.

Peltola, H. 1996a. Model computations on wind flow and turning moment by wind for Scots pines along the margins of clear-cut areas. Forest Ecology and Management 83(3):203–215.

Peltola, H. 1996b. Swaying of trees in response to wind and thinning in a stand of Scots pine. Boundary-Layer Meteorology 77:285–304.

Peltola, H., and D. Kellomaki. 1993. A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. Silva Fennica 27(2):99–111.

Peltola, H., D. Kellomaki, A. Hassinen, M. Lemettinen, and J. Aho. 1993. Swaying of trees as caused by wind: analysis of field measurements. Silva Fennica 27(2):113–126.

Peltola, H.M. 2006. Mechanical stability of trees under static loads. American Journal of Botany 93(10):1341–1351.

Petty, J.A., and C. Swain. 1985. Factors influencing stress breakage of conifers in high winds. Forestry 58:75–84.

Reiterer, A., H. Lichtenegger, S. Tschegg, and P. Fratzl. 1999. Experimental evidence for a mechanical function of the cellulose microfibril angle in wood cell walls. Philosophical Magazine A 79:2173–2184.

Rodgers, M., A. Casey, C. McMenamin, and E. Hendrick. 1995. An experimental investigation of the effects of dynamic loading on coniferous trees planted on wet mineral soils. pp. 204–219. In: M.P. Coutts and J. Grace (Eds.). Wind and Trees. Cambridge University Press, Cambridge, UK.

Rodriguez, M., E. de Langre, and B. Moulia. 2008. A scaling law for the effects of architecture and allometry on tree vibration modes suggests a biological tuning to modal compartmentalization. American Journal of Botany 95:1523–37.

Rodriguez, M., S. Ploquin, B. Moulia, and E. de Langre. 2012. The multimodal dynamics of a walnut tree: experiments and models. Journal of Applied Mechanics 79(4):1–5.

Roodbaraky, H.J., C.J. Baker, A.R. Dawson, and C.J. Wright. 1994. Experimental observations of the aerodynamic characteristics of urban trees. Journal of Wind Engineering and Industrial Aerodynamics 52:171–184.

Ruck B., C. Kottmeier, C. Matteck, C. Quine, and G. Wilhelm (Eds.). 2003. Proc. Int. Conf. Wind Trees. University of Karlsruhe, Germany.

Rudnicki, M., S.J. Mitchell, and M.D. Novak. 2004. Wind tunnel measurements of crown streamlining and drag relationships for three conifer species. Canadian Journal of Forestry Research 34:666–676.

Rudnicki, M.R., T.H. Meyer, V.J. Lieffers, U. Silins, and V.A. Webb. 2008. The periodic motion of lodgepole pine tree as affected by collisions with neighbors. Trees 22:475–482.

Salmen, L. (Ed). 2006. Proc. 5th Plant Biomech. Conf. Stockholm: STFI

Saunderson, S.E.T., A.H. England, and C.J. Baker. 1999. A dynamic model of the behavior of sitka spruce in high winds. Journal of Theoretical Biology 200:249–259.

Schelhaas, M.J. 2008. The wind stability of different silvicultural systems for Douglas-fir in the Netherlands: A model-based approach. Forestry 81(3):399–414.

Schindler, D. 2008. Responses of Scots pine trees to dynamic wind loading. Agricultural and Forest Meteorology 148:1733–1742.

Schindler, D., J. Bauhus, and H. Mayer. 2012. Wind effects on trees. European Journal of Forest Research 131:159–163.

Schindler, D., R. Vogt, H. Fugmann, M. Rodriguez, J. Schonborn, and H. Mayer. 2010. Vibration behavior of plantation-grown Scots pine trees in response to wind excitation. Journal of Agricultural and Forest Meteorology 150:984–993.

Sellier, D., and T. Fourcaud. 2009. Crown structure and wood properties: Influence on tree sway and response to high winds. American Journal of Botany 96:885–896.

Sellier, D., T. Fourcaud, and P. Lac. 2006. A finite element model to investigate the effects of aerial architecture on tree oscillations. Tree Physiology 26:799–806.

Sellier, D., Y. Brunet, and T. Fourcaud. 2008. A numerical model of tree aerodynamic response to a turbulent airflow. Forestry 81:279–97.

Smiley, E.T., and B. Kane. 2006. The effects of pruning type on wind loading of *Acer rubrum*. Arboriculture & Urban Forestry 32:33–40.

Smiley, E.T., and K. Coder. 2002. How Trees Stand up and Fall Down. Tree Structure & Mechanics Conference Proceedings. ISA pub. Urban tree biomechanics conference proceedings from Savannah, Georgia.

Smiley, E.T., N. Matheny, and S. Lilly. 2011. Best Management Practices Tree Risk Assessment. ISA, Champaign, Illinois, U.S.

Spatz H.-C, F. Bruchert, and J. Pfisterer. 2007. Multiple resonance damping or how do trees escape dangerously large oscillations? American Journal of Botany 94:1603–11.

Spatz, H.C., and B. Theckes. 2013. Oscillation damping in trees. Plant Science 207:66–71.

Spatz, H.C., and F. Brüchert. 2000. Basic biomechanics of self-supporting plants: wind and gravitational loads on a Norway spruce tree. Forest Ecology Management 135:33–44.

Spatz, H.-C.H. 2000. Greenhill's Formula for the Critical Euler Buckling Length revisited. In: H.-C.H. Spatz and T. Speck (Eds.). 3rd Plant Biomechanics.

Spatz, H.-C.H., and O. Speck. 2002. Oscillation frequencies of tapered plant stems. American Journal of Botany 89:1–11.

Speck, O., and H-C. Spatz. 2004. Damped oscillations of the giant reed *Arundo donax* (Poaceae). American Journal of Botany 91(6):789–796.

Speck, T, and I. Burgert. 2011. Plant Stems: Functional Design and Mechanics. Annual Review of Material Research 41:169–193.

Stacey, G. R., R.E. Belcher, C.J. Wood, and B.A. Gardiner. 1994. Wind and wind forces in a model spruce forest. Boundary-Layer Meteorology 69:311–334.

Sugden, M.J. 1962. Tree sway period: A possible new parameter for crown classification and stand competition. Forestry Chronicle 38:336–344.

Telewski, F.W., L. Kohler, and F. Ewers (Eds.). 2003. Proc. 4th Int. Plant Biomech. Conf. East Lansing: Michigan State Univ.

Tevar Sanz, G., A. Sanz-Andres, M. Fernandez Canadas, and M.A. Grande Ortiz. 2003. Wind effects on *Populus* sp. In: Wind Effects on Trees. University of Karlsruhe, Germany.

Theckes, B., E. de Langre, and X. Boutillon. 2011. Damping by branching: A bioinspiration from trees. Bioinspiration and Biomimetics 6:1–11.

Thibaut, B. (Ed.). 2012. Proceedings of the 6th Plant Biomechanics Conference, Cayenne, French Guyana.

Vogel, S. 1989. Drag and Reconfiguration of Broad Leaves in High Winds. Journal of Experimental Biology 40(217):941–948.

Vogel, S. 1996. Blowing in the Wind: Storm-resisting features of the design of trees. Journal of Arboriculture 22(2):92–98.

Vollsinger, S., S.J. Mitchell, K.E. Byrne, M.D. Novak, and M. Rudnicki. 2005. Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. Canadian Journal of Forestry Research 35:1238–1249.

Wessolly, L. 1991. Verfahren zur Bestimmung der Stand- und Bruchsicherheit von Bäumen [Methods for determining the safety against uprooting and stem fracture]. Holz als Roh- und Werkstoff 49:99–104.

Wood, C.J. 1995. Understanding wind forces on trees. In: M.P. Coutts and J. Grace (Eds.). pp. 133–164. Wind and Trees. Cambridge University Press, Cambridge, UK.

Wood, M.J., R. Scott, P.W. Volker, and D.J. Mannes. 2008. Windthrow in Tasmania, Australia: Monitoring, prediction, and management. Forestry 81(3):415–427.

Zeng, H., T. Pukkala, and H. Peltola. 2007. The use of heuristic optimization in risk management of wind damage in forest planning. Forest Ecology and Management 241:189–199.

Zhu, J., T. Matsuzaki, and K. Sakioka. 2000. Wind speed within a single crown of Japanese black pine (*Pinus thunbergii* Parl.). Forest Ecology and Management 135:19–31.

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Résumé. Un examen de la documentation sur les études biomécanique des arbres à l'aide de méthodes d'analyse dynamique est effectué. L'accent est mis sur la biomécanique des arbres cultivés à l'air libre que l'on trouve généralement dans les zones urbaines plutôt que dans les forêts ou les plantations. La distinction n'est pas effectuée sur les espèces mais sur leur forme, car les arbres cultivés à l'air libre se développent habituellement avec une masse de branche considérable et leur réponse dynamique aux vents est certainement différente que celle d'autres formes d'arbres. Des méthodes d'analyse dynamique appliquées aux arbres sont examinées. Des modèles d'arbres simples ont été développés pour comprendre leurs réponses dynamiques, mais ceux-ci ignorent la dynamique des branches. Des modèles plus complexes et des analyses par éléments finis sont en train de développer une approche multimodale pour représenter la dynamique de branches d'arbres. Les résultats indiquent que les propriétés des constituants jouent un rôle limité dans la dynamique des arbres. Les paramètres qui peuvent influencer leur dynamique sont la forme et la morphologie de l'arbre lui-même et de ses branches.

Zusammenfassung. Hier werden Studien zur Baummechanik betrachtet, die dynamische Analysemethoden verwenden. Der Fokus dieses Überblicks liegt bei der Biomechanik von frei wachsenden Bäumen, wie sie üblicherweise in urbanen Räumen angetroffen werden, im Vergleich zu eng stehenden Wald- oder Plantagenbäumen. Der Unterschied basiert nicht auf der Baumart, sondern in der Form, weil frei wachsende Bäume gewöhnlich eine breite Krone ausbilden und die dynamische Reaktion bei Windlast anders ist als bei anderen Baumkronenformen. Verschiedene angewendete Methoden zur dynamischen Analyse werden vorgestellt. Einfache Baummodelle wurden entwickelt, um die dynamische Reaktion von Bäumen zu verstehen, aber diese ignorieren größtenteils die Dynamik der Äste. Komplexere Modelle und begrenzte Analysen der Elemente entwickeln einen multimodalen Ansatz zur Repräsentation der Ast-Dynamik bei Bäumen. Die Ergebnisse verdeutlichen, dass die Materialeigenschaften nur eine begrenzte Rolle dabei spielen und es ist die Form und Morphologie der Bäume und Äste, die die Dynamik des Baumes beeinflussen kann.

Resumen. Se revisan estudios de biomecánica del árbol utilizando métodos dinámicos de análisis. El énfasis es sobre la biomecánica de los árboles que crecen a campo abierto, que típicamente se encuentran en zonas urbanas, antes que aquellos de bosques o plantaciones. La distinción no se basa solo en especies, sino en su forma, ya que los árboles en áreas abiertas por lo general crecen con una considerable masa de ramas y la respuesta dinámica de los vientos puede ser diferente a otras formas de los árboles. Son revisados los métodos de análisis dinámicos aplicados a los árboles. Se han desarrollado modelos simples para entender las respuestas dinámicas de los árboles, pero éstos ignoran en gran medida la dinámica de las ramas. Modelos más complejos y los análisis de elementos finitos están desarrollando un enfoque multimodal para representar la dinámica de las ramas de los árboles. Los resultados indican que las propiedades de los materiales juegan un papel limitado en la dinámica de los árboles y que es más bien la forma y la morfología del árbol y de las ramas las que lo pueden estar haciendo.