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Mechanical stability of trees under dynamic loads[1]

Kenneth R. James,[2,5] Nicholas Haritos,[4] and Peter K. Ades[3]

[2]School of Resource Management, Faculty of Land and Food Resources, University of Melbourne, Melbourne, Australia, 3001;
[3]School of Forest and Ecosystem Science, Faculty of Land and Food Resources, University of Melbourne, Australia, 3001; and
[4]Civil and Environmental Engineering, University of Melbourne, Australia, 3001

Tree stability in windstorms and tree failure are important issues in urban areas where there can be risks of damage to people and property and in forests where wind damage causes economic loss. Current methods of managing trees, including pruning and assessment of mechanical strength, are mainly based on visual assessment or the experience of people such as trained arborists. Only limited data are available to assess tree strength and stability in winds, and most recent methods have used a static approach to estimate loads. Recent research on the measurement of dynamic wind loads and the effect on tree stability is giving a better understanding of how different trees cope with winds. Dynamic loads have been measured on trees with different canopy shapes and branch structures including a palm (*Washingtonia robusta*), a slender Italian cypress (*Cupressus sempervirens*) and trees with many branches and broad canopies including hoop pine (*Araucaria cunninghamii*) and two species of eucalypt (*Eucalyptus grandis, E. teretecornus*). Results indicate that sway is not a harmonic, but is very complex due to the dynamic interaction of branches. A new dynamic model of a tree is described, incorporating the dynamic structural properties of the trunk and branches. The branch mass contributes a dynamic damping, termed mass damping, which acts to reduce dangerous harmonic sway motion of the trunk and so minimizes loads and increases the mechanical stability of the tree. The results from 12 months of monitoring sway motion and wind loading forces are presented and discussed.

Key words: damping; dynamics; loads; model; spectrum; stability; tree; wind.

Tree stability in windstorms and tree failure are important issues in urban areas where there can be risks of damage to people and property. Trees are a valuable resource that can benefit people and improve the quality of life, often having important historical or cultural significance. Current methods of managing urban trees, such as pruning and assessing mechanical strength, are mainly based on visual assessment or the previous experience of people such as trained arborists. Trees, especially large ones, need careful management in urban areas where failure can result in loss of life or damage to property (Fig. 1). Serious liability issues can arise if there is a perception that poor or negligent tree care practices have contributed to tree failure. Managers have only limited data available to use when trying to assess tree strength and stability. Some limited use of static pull tests on trees occurs in Europe, but is not widely adopted in other parts of the world. Trees in forests and plantations experience damaging winds and need management to produce quality timber, as well as protection to maintain habitat and contribute to the wider global environment. Recent research on measuring dynamic wind loads on actual trees is giving a better understanding of how different trees cope with winds.

The size of trees and their architecture (shape and structure) greatly influence their mechanical stability under dynamic loading. As trees grow, the added biomass develops greater self-loading and the upper parts of the tree are exposed to higher wind speeds creating larger bending moments at its base (Niklas and Spatz, 2000). The growth of trees is largely determined by physiological constraints, particularly those affecting photosynthesis and water transport, but even if these are not exceeded, limitations of size and shape are still imposed by biomechanical constraints (Spatz and Bruechert, 2000).

A tree must be able to withstand all the physical loads throughout its life. For nearly all trees, the greatest load is from the wind that comes as gusts of rapid, periodic, dynamic events. Wind is the most persistent of the harmful natural forces to which any individual tree or forest stand is subjected (Jacobs, 1936). There may be some exceptions, such as trees that grow deep in rain forests and never experience large wind forces or trees that fail under heavy ice and snow loading. However, in most situations wind constantly influences the tree from germination until death (Jacobs, 1936). Dynamic forces are important when trees grow to large sizes because if there is enough wind, the structural demands on the trunk, branches, and roots approach critical limits, which, if exceeded, will result in failure.

In this paper, we take an engineering approach to mechanical stability, focusing on large trees, with the underlying concept that all plants must obey well-known biological and physical laws. We review experimental results and models that have been applied in the past, then introduce a new dynamic model of a tree that incorporates the effect of branches, which dampen the motion the tree as a whole and increase its stability under extreme wind loadings. Data of wind loads from actual trees are presented, which is consistent with the newly proposed conceptual model.

REVIEW OF PREVIOUS STUDIES

The mechanical properties of trees have been of interest for centuries. In 1634, Galileo discussed the problem of scaling

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[5] Author for correspondence (e-mail: kenj@unimelb.edu.au, tel 613 9250 6800)

Fig. 1. Storm damage. *Catalpa bignonioides* after wind storm, February 2005, Royal Botanic Gardens, Melbourne, Australia. (Photo by Kiah Martin).

and strength and noted that as machinery became larger, with its geometrical proportions maintained, the larger machines failed whilst the smaller machines survived (Seeger, 1966). Galileo stated, "For every machine and structure, whether artificial or natural, there is set a necessary limit beyond which neither art nor nature can pass, it is here understood of course, that the material is the same and the proportion preserved." Galileo (Galilei, 1638, pp. 3, 4) had a good understanding of the size limits of trees and noted "that an oak two hundred cubits high would not be able to sustain its own branches if they were distributed as in a tree of ordinary size."

A quantitative structural analysis of a tree was attempted by Leonard Euler and later Greenhill in 1881. Both used static analyses to calculate the maximum critical height of a tree, above which it failed under its own weight (Spatz, 2000). A simple model was used to approximate a tree (Fig. 2a) that was considered as a tapered pole made of a homogeneous material. Other early plant biomechanical studies from 1874 have been reviewed by Spatz and Bruechert (2000).

Modifications to the simple tree model include representing the canopy as a lumped mass on a column (Sanderson et al., 1999), representing the tree as two masses (one for the canopy and one for the root-soil system) and the trunk as a weightless elastic column (Baker, 1995), and modeling the tree as a series of *n* logs with lumped masses representing branch whorls along the trunk (Fig. 2b, Guitard and Castera, 1995). A summary of studies using the simple model is provided by Moore and

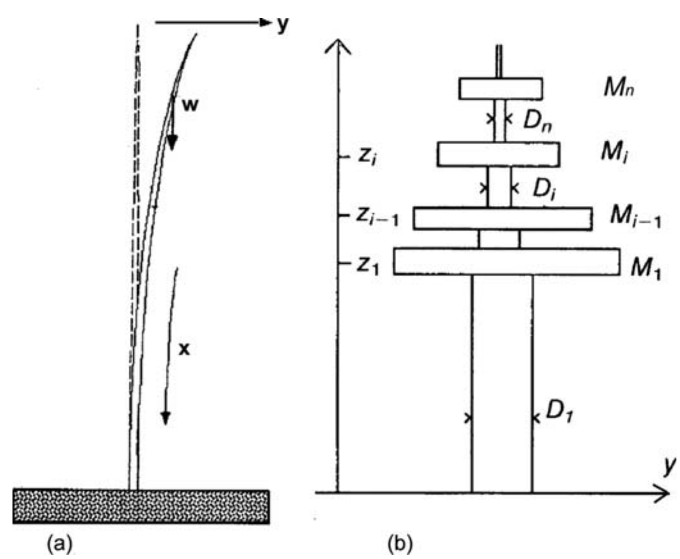

Fig. 2. Two simplified tree models. (a) Simple tree model from Greenhill 1881; *x*-coordinate runs from 0 at top of pole, *y*-transverse coordinate, *w*: weight (Spatz 2000). (b) Modified simple tree model with stem divided into *n* logs of *i* elements, *z*: height, *M*: weight, *D*: diameter (Guitard and Castera, 1995).

Maguire (2005). Simplified tree models do not consider the dynamic interaction of branches and can only approximate the many urban tree species that have several main stems and substantial branches. In particular, the branches need to be considered as dynamic coupled cantilevers and not simply as lumped masses (Kerzenmacher and Gardiner, 1998).

More recently, a number of authors have undertaken static analyses of tree behavior under an applied load. Niklas (1992) summarizes these, the history of plant biomechanics more generally, and describes how basic principles of structural engineering theory can be applied to the study of plant forms. In many studies of trees and wind, simplifying assumptions are often made; however, in reality the response of trees to wind loading is complex. Storm winds are never constant, with gusts constantly changing in both speed and direction, and trees respond with a complex oscillating motion of the leaves, branches, and trunk, all of which move in different directions as the canopy sways. Field measurements of trees swaying have been studied by a number of authors such as Sugden (1962), Mayhead (1973), Mayer (1987), Holbo et al. (1980), Blackburn et al. (1988), Milne (1991), Peltola et al. (1993), Gardiner (1995), Baker (1997), Hassinen et al. (1998), Flesch and Wilson (1999), Kerzenmacher and Gardiner (1998), Spatz and Bruechert (2000), Rudnicki et al. (2001), Moore (2002), Sellier and Fourcard (2005), and Moore and Maguire (2005).

All these studies have used one of two main methods to measure sway. The first method induces sway in still air conditions by pulling then releasing the tree with a rope and measuring the resulting (short duration) sway motion—the so-called "pluck test." This is a useful test to measure some vibration parameters and to test models against field data for validation. The second method measures tree sway under real wind conditions. There is a fundamental difference between these two methods in the way energy is transferred to the tree. The rope method pulls at a single point, and energy is first stored in the bent trunk then suddenly released as the trunk returns to the rest position. This never happens in nature. For real trees, wind pushes on the broad tree canopy, and energy is transferred in a pulsating, dynamic manner over long periods of time.

A single forest tree (*P. sylvestris*), height 11.1 m, under actual wind conditions was monitored by Hassinen et al. (1998) in Finland, using a prism-based system. The tree sway movement was extremely complicated and quite different from the pull and release sway motion. Spectral analysis (fast Fourier transforms) was used to determine the tree's frequency response and indicated a preferred peak at 0.2 Hz with a second peak at 1.85 Hz, almost certainly indicating a second mode of vibration. However, the graphs of the stem displacement spectra were not smooth, indicating many other frequencies were present. These may be due to oscillation of the branches, but no comment was made on the influence of branches on the tree sway.

Baker (1997) measured sway motion on 62 urban trees using laser beams targeted on the trunk of the tree below the canopy. Tree height varied from 4.7 to 19.5 m. The tree sway data indicated three distinct types of spectra corresponding to three different geometries of tree and were designated types I, II, and III. Type I spectra had low frequency peaks between 0.3–0.6 Hz in summer and 0.5–1.5 Hz in winter. Type II had no significant natural frequency for either summer or winter conditions. Type III was similar to type I but with a significantly lower natural frequency range for similar diameter trees. The three different tree geometries were type I, normal geometry of limes with main branches coming from the trunk at angles around 20–30 degrees to the vertical, Type II being the "bushy" type of tree with a well-developed crown and Type III having steeply inclined main branches at angles of less than 10 degrees to the vertical. Significantly, for any one tree size, there is a fairly wide spread of values that Baker suggested might reflect the different nature of the root systems. It may be the dynamic interaction of the branches broadening the range of natural frequencies that may also explain the spread of data. Pruning a canopy and branch removal affects the wind load on a tree, but how this affects stability is not fully understood. Systematic pruning does not greatly affect the damping ratio until around half the silhouette area of the crown is removed (Mayhead et al., 1975). In a review of previous studies on tree sway, Moore and Maguire (2004) described the effect of branch removal on sway frequency. Removal of branches in the top of the crown appeared to have the greatest effect, with up to 80% of the crown mass needing to be removed before an increase in the natural frequency is noticeable. Moore and Maguire (2005) showed that changes in natural frequency with crown removal did not appear to be due to changes in damping ratio, but rather to changes in mass distribution of the trees. They further suggested that representing the crown as a series of lumped masses as they did in their model might not be appropriate and that further work is required to model the branches of a tree as individual damped harmonic oscillators coupled to the main stem.

A dynamic structural analysis is usually more complex than a static analysis and care must be taken not to make assumptions that oversimplify the analysis or important transient forces may be missed. The dynamic interaction of branches is critical in understanding the dynamic response of the tree in winds, but studies have been limited due to the complexity involved. The importance of branches can be summarized in the statement, "a tree without branches is not a tree" (Shigo, 1986, p. 208). Each branch is a mass that sways in the wind and dynamically interacts with other branches and the trunk in a complex way. This interaction between the components of the crown can prevent the generation of natural harmonic sway frequencies and minimize extreme dynamic loads that would potentially cause mechanical failure.

MATERIALS AND METHODS

A new dynamic structural model for a tree is presented (Fig. 3), and data from actual trees (Table 1) has been collected to test the model. Trees were selected to represent different architectural types to study how wind loading varied between pole-like trees and those with a complex canopy of many branches. The model consists of dynamic masses that separately represent the trunk, main branches, and subbranches. Each structural member is considered as an individual dynamic oscillating mass (m), attached via a spring (k) and a damper (c) to its base. The trunk is attached at its base to the root–soil system and values for its mass, spring constant, and damping can be put into the model. The main branches are attached to the trunk (1st order branch), and subsequent branches (2nd order, etc.) attach in turn to their supporting branch. Each branch and subbranch can be assigned its own value for mass, spring constant, and damping.

The significant difference of this model is that branches are considered as dynamic oscillating masses, which interact with the trunk and dynamically modifies the overall sway motion. The model can describe tree shapes of different architecture and allows for different levels of complexity to be studied. The model (Fig. 3b) can be drawn to resemble the structural elements of a tree (Fig. 3a) and in the extreme could be adapted to include all branches and foliage.

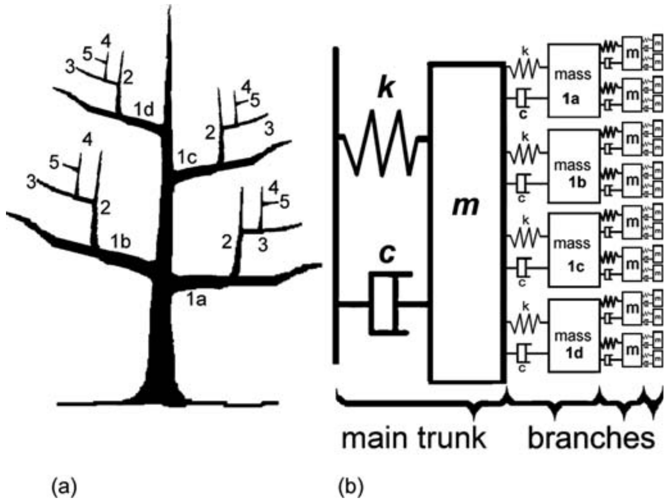

Fig. 3. Dynamic structural model of a tree, with trunk and branches represented as dynamic masses attached to each other. Numbering system: 1 represents a 1st order branch attached to the trunk, 2 represents a 2nd order branch attached to a 1st order branch, and so on. Letters a, b, c, and d represent different branches of the same order (c, damping factor; k, spring constant; m, mass).

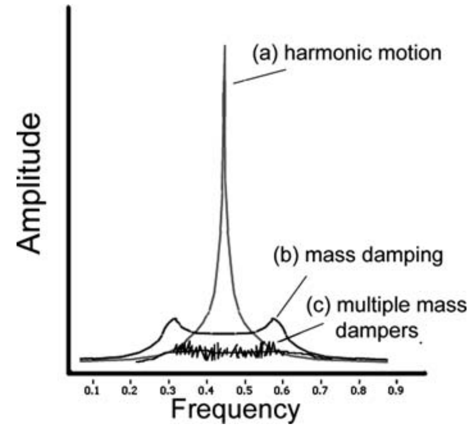

Fig. 4. The effect of mass damping on dynamic sway motion of trunk. (a) No mass damping and large peak, (b) one branch (mass damper) with two small peaks, (c) many mass dampers showing the no peak amplitude.

The example shown in Fig. 3 represents an approximation of a tree, with a central columnar trunk and four main branches attached (shown as 1a, 1b, 1c, and 1d). These main branches are considered as 1st order branches and given the number 1. Second order branches can be represented on the model and even 3rd, 4th, and 5th order branches can be added if necessary. The smaller branches will have less effect due to their smaller mass but collectively can be important to the dynamic performance of the tree because of their contribution to (aerodynamic) damping. A simplified version of this model was presented by James (2003).

Elements of the model—There are three elements of the dynamic model. (1) Mass (m)—each oscillating mass can be separately considered, i.e., the trunk, main branches, subbranches, and so on. (2) Spring constant (k)—a property of the material (wood) that can vary with age and position on a tree (related to Young's modulus). (3) Damping factor (c)—a complex quantity consisting of aerodynamic damping (energy dissipation by movement through the air) and viscoelastic damping (energy dissipation from internal factors such as root/soil movement and internal wood energy dissipation).

Effect of branches on dynamic sway of trees—A simple unbranched structure such as a pole or the tree model in Fig. 2a will have a regular period of oscillation and a defined natural frequency. If dynamic forces are applied to the structure at this natural frequency, large sway amplitudes occur, which are shown as a peak in the frequency response graph in Fig. 4a. This is known as the resonant frequency and causes harmonic motion that is potentially dangerous in structures because large sway motions result in large internal forces and energy transfers and can cause failure. Some of the most spectacular cautionary examples in structural engineering have been bridges that resonated at frequencies created by wind gusts or vortices.

TABLE 1. Trees species and dimensions used in field measurement of dynamic wind loads.

Species	Location	Height (m)	Diameter dbh (m)
Araucaria cunninghamii	Burnley, Melbourne	22.0	0.79
Araucaria cunninghamii	Burnley, Melbourne	19.0	0.94
Araucaria cunninghamii	Burnley, Melbourne	23.5	0.87
Cupressus sempervirens	Burnley, Melbourne	17.0	0.23
Eucalyptus grandis	Burnley, Melbourne	19.3	0.52
Washingtonia robusta	Burnley, Melbourne	18.1	0.44
Eucalyptus teretecornus	Sale, Victoria	14.0	0.84
Eucalyptus teretecornus	Sale, Victoria	14.0	0.88

Trees are not like poles because they have many branches attaching to the trunk, and resonance has not been reported. The branches sway separately to the trunk and greatly modify the sway amplitude of the trunk. The swaying mass can be called a mass damper because it reduces, or dampens, the sway of the structure. Mass damping is a feature of this dynamic model and occurs when an oscillating branch sways on an oscillating trunk. The mass damper (or the branch) has its own mass, spring constant, and damping factor. The dynamic effect of a mass damper (the branch) on the amplitude of oscillation of the trunk is dramatic, provided the branch is big enough to have a resonant frequency similar to that of the trunk. The effect of the mass damper is to cause a strong dynamic interaction between the trunk mass (m) and the branch mass (m_1). The previous large amplitude of the trunk oscillation now becomes smaller at two frequencies, one sightly below and one slightly above the original frequency. This split mode results in a greatly reduced amplitude of sway. The oscillating energy of the structure partly transfers into the mass damper, which can dissipate the energy through the damper d_1. The dramatic decrease in amplitude of these two "split modes" is shown in Fig. 4b, (Den Hartog, 1956). If many mass dampers occurred on a structure, such as a tree with many branches, the expected sway amplitudes would be further reduced to a flat curve similar to the curve of Fig. 4c.

A concept, called multiple tuned mass dampers, has been investigated in earthquake engineering literature (Abe and Fujino, 1994) and is effective in minimizing the sway motion of structures oscillating due to earthquakes. Most trees have a complex structure with many branches (1st order, 2nd, 3rd, etc.), all of which dynamically interact as mass dampers. The 1st order branches are themselves mass damped by 2nd order branches. This is equivalent to adding a mass damper to the first mass damper and will smooth out the sway of the first branch. Smaller branches also affect the 2nd order branch and these smaller branches are in turn branched until a network of branches is created. The overall effect minimizes the dynamic sway of the tree in winds by creating a broad range of frequencies (Fig. 4c) and prevents the main structure of the tree trunk from developing large and potentially dangerous harmonic sway motions.

The idea of a broad range of natural frequencies being generated by the interaction of the limbs with the trunk was supported by data of Moore (2002), who investigated the effect of removing branches from Douglas fir trees. Branch damping seemed effective until at least 80% of the crown mass was removed. When only 20% of branches remained, sway amplitudes began to increase noticeably. This indicated the important influence of side limbs and that only a few branches are needed to make a significant change in the sway motion of a tree trunk. Moore and Maguire (2005) reported further work supporting this idea and suggested that the effect of crown removal on increasing natural frequency is due to mass removal rather than changes in damping.

Field measurement of wind forces on trees—Data were collected from actual trees to test this new conceptual model. New instruments were designed and constructed to measure the sway motion of trees in the wind. The strain

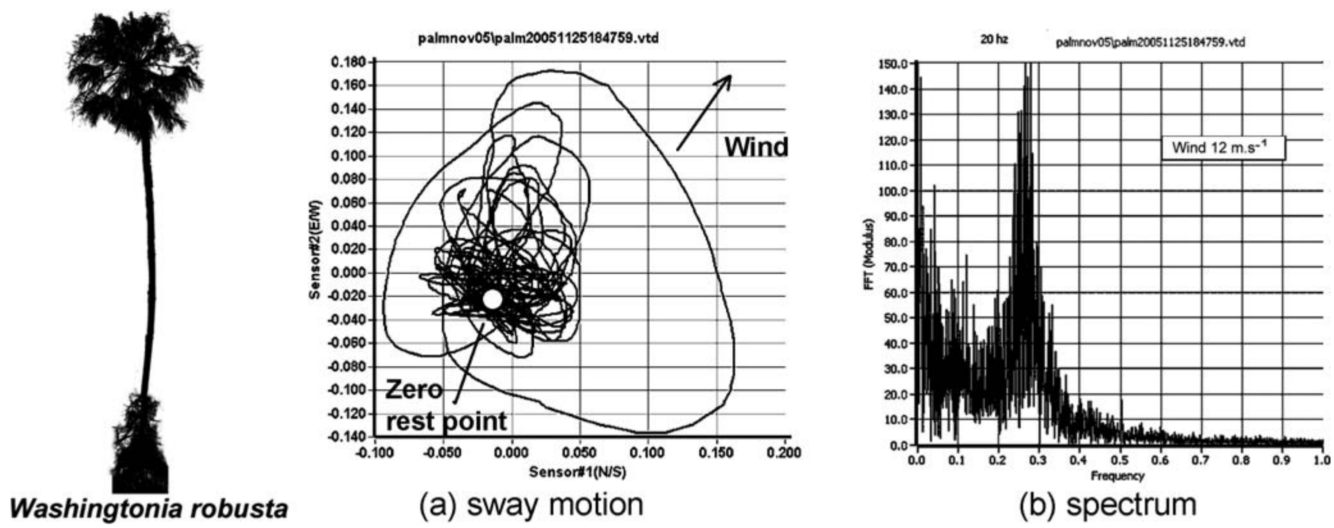

Fig. 5. Sway motion of *Washingtonia robusta* (wind speed average 12 m·s^{-1}) showing (a) looping sway motion (5 minute period) and (b) spectrum (from fast Fourier transformation, 30 minutes) showing sway frequency with single peak at 0.28 Hz. *Note*: Vertical scale is indicative only and depends on algorithm used.

meters were 500 mm long and accurate to 1 μm giving a strain resolution of 2×10^{-6}. As the tree bends in the wind, the outer fibers stretch on the windward side and compress on the leeward side. This small fiber movement can be measured by the strain meters and logged to a computer. Two meters were attached to the trunk, one to measure movement in the north–south direction, and the second located to measure the movement in the east–west direction, so a complete record of sway motion is obtained in all directions. Because wind direction is variable, two sensors oriented in this way are required to monitor the full motion of the tree. Sensors were monitored at a frequency of 20 Hz during windstorm events to ensure that higher frequency oscillations were recorded. The movement can be presented on an XY (EW–NS) graph to show the full complex motion of the tree sway (Fig. 5a). Similar graphs of tree movement have been presented by Gardiner (1995) and Moore and Maguire (2005) but at lower sampling frequencies so the full complexity of the two dimensional motion is not always apparent.

Eight trees were monitored over 12 months, and the results of wind storm events were recorded to a computer at 20 Hz. Software triggered the recording of strain in two directions (NS and EW), wind speed, wind direction, temperature, and humidity so that storm events were automatically recorded. The trees were located in Victoria, Australia, and details of tree species and dimensions are given in Table 1.

Each tree was calibrated using a static pull test so that wind loading on the tree could be determined from the sensor readings. Calibration was performed by applying a series of known bending moments to the tree, through a rope attached midway up the stem, and measuring the resulting strain. A calibration graph was produced for each tree that enabled the sensor readings to be converted into the wind load acting on the tree. Young's modulus was also determined during the static pull tests by measuring the cross-sectional area of the trunk at the sensor attachment point and calculating the moment of inertia as described in Timoshenko (1955) and Niklas (1992). Preliminary work using this method shows values of Young's modulus within the range of living trees (2.37–4.44 GN·m^{-2}) similar to those reported by Morgan and Cannell (1987), Milne and Blackburn (1989), Niklas (1992), Mencuccini et al. (1997), Bruchert and Gardiner (2000), Peltola et al. (2000), and Silins et al. (2000).

Hundreds of hours of data have been recorded, and a selection of the extreme events is summarized in this paper. Wind loads were determined from the tree calibration data. A spectral analysis was used to analyze the sway motion and identify any dominant natural frequency using a fast Fourier transformation method.

The sensors were calibrated in a laboratory to determine their dimensional accuracy and frequency response. Each sensor was attached to a vibrating arm and vibrated under a known frequency. The vibration response was linear up to 12 Hz, and the sampling was standardized to 20 Hz so that the expected frequencies of tree sway (up to 2 Hz) were within the limits of the sensors.

RESULTS

The most pole-like tree studied is the palm (*Washingtonia robusta*) that has no branches. The Italian cypress (*Cupressus sempervirens*) was the next most slender tree with branches closely aligned to the trunk. Trees with a central trunk structure and many branches were represented by three similar hoop pines (*Araucaria cunninghamii*), and finally trees with many branches and no central trunk were represented by the eucalypts (*Eucalyptus grandis* and *E. teretecornus*).

The sway of motion of *W. robusta*, is shown in Fig. 5. There is pronounced looping and back-and-forth motion past a zero point. The palm has a very flexible response to the wind, and significant sideways movement occurs during the looping sway motion. A fast Fourier transformation (FFT) analysis shows a clearly defined peak (Fig. 5b) that indicates the palm sways with a natural frequency of 0.28 Hz. There are no branches to dynamically interact with the main trunk and damp oscillations, but the canopy of fronds provide some damping of the sway motion, even though they have relatively small mass compared to the trunk.

The Italian cypress (*Cupressus sempervirens*) is a tree of very narrow upright architecture with a shape resembling a single central column. An Italian cypress of height of 17.0 m and diameter at breast height (dbh) of 0.23 m was monitored during medium winds. The motion was again complex (Fig. 6a), and the FFT analysis (Fig. 6b) revealed two distinct peaks that indicated two modes of sway: a primary mode at 0.26 Hz and a secondary mode at 0.66 Hz. This tree has a flexible response to wind loading and bends in the wind to survive. The secondary sway mode is quite visible under wind loading and appears to be unusual in trees. It is likely to be a mechanism for reducing failure in windstorms. Hassinen et al. (1998) reported a similar complex sway on an 11.1 m Scots pine (*Pinus sylvestris*) with a primary sway frequency of 0.2 Hz and a secondary peak at 1.85 Hz.

Three hoop pines (*Araucaria cunninghamii*) of similar age and approximately 20 m high were monitored over several months, and a sample of data from a windstorm is shown in Fig. 7. The sway motion is mainly in the direction of the wind

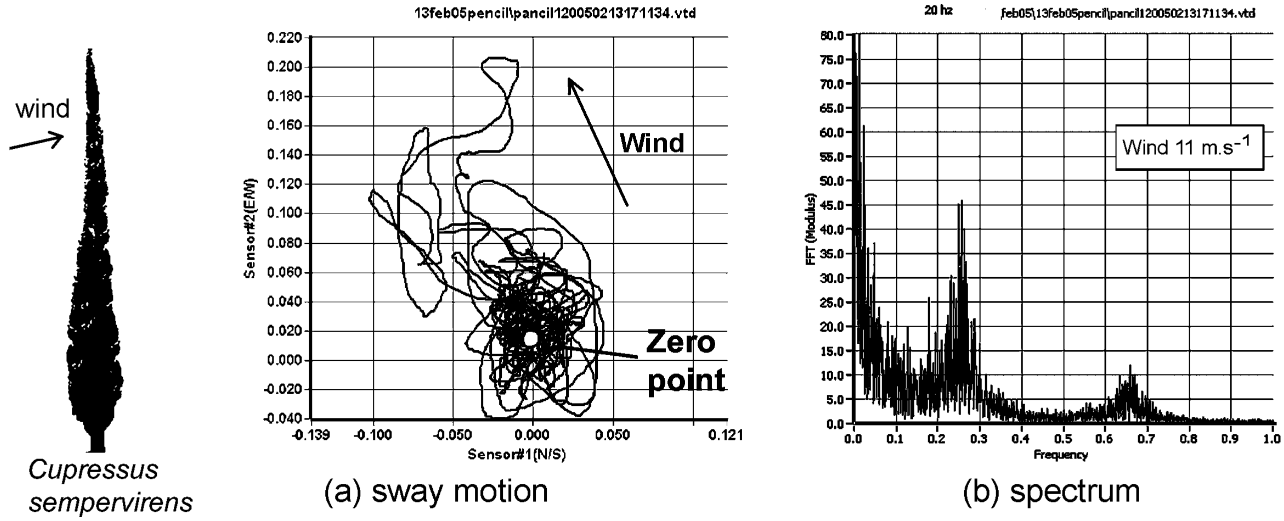

Fig. 6. Sway motion of *Cupressus sempervirens* (wind speed average 11 m $\cdot$ s^{-1}) showing (a) complex sway motion and (b) spectrum showing sway frequency with two peaks at 0.26 Hz and 0.66 Hz (2nd mode of sway).

with some looping and sideways movement occurring. The tree never sways back past its zero or rest point, i.e., back into the wind. The more the wind blows, the more the tree bends and sways away from the wind. The spectral analysis shows a range of natural frequencies but there was a distinct peak for each tree. The FFT spectra for the three trees had peaks at 0.29 Hz, 0.30 Hz, and 0.40 Hz, and no secondary peaks occurred. The peak indicates that the main central trunk is the dominant mass oscillating at its natural frequency, and the branches, although smaller in mass, are sufficient to dampen and detune the trunk sway motion. The FFT peak is much smaller and wider for the hoop pine than for the palm and is consistent with the dynamic damping effect of the branches. Side limbs of this species have a small mass compared to the mass of the main trunk but still contribute significant mass damping.

Trees with many branches and relatively small trunk mass were represented by a flooded gum (*Eucalyptus grandis*) and two red gums (*E. teretecornus*). These trees were monitored for 3 months, and a sample of the sway motion of the *E. teretecornus* during winds of 17 m $\cdot$ s^{-1} is shown in Fig. 8. This tree was 14.0 m high, had dbh of 0.84 m with a spreading canopy of many branches and no central trunk. The sway motion is similar in all three trees and is always down wind with a complex pattern. The spectral analysis showed a broad peak at 0.32 Hz, with many other closely spaced sway frequencies present. This is consistent with the dynamic response of a tree with many large side branches, that prevent any large oscillations with dangerous harmonic sways.

DISCUSSION

Dynamic tree sway in winds appears to be greatly influenced by the dynamic sway of the branches. As the proportion of

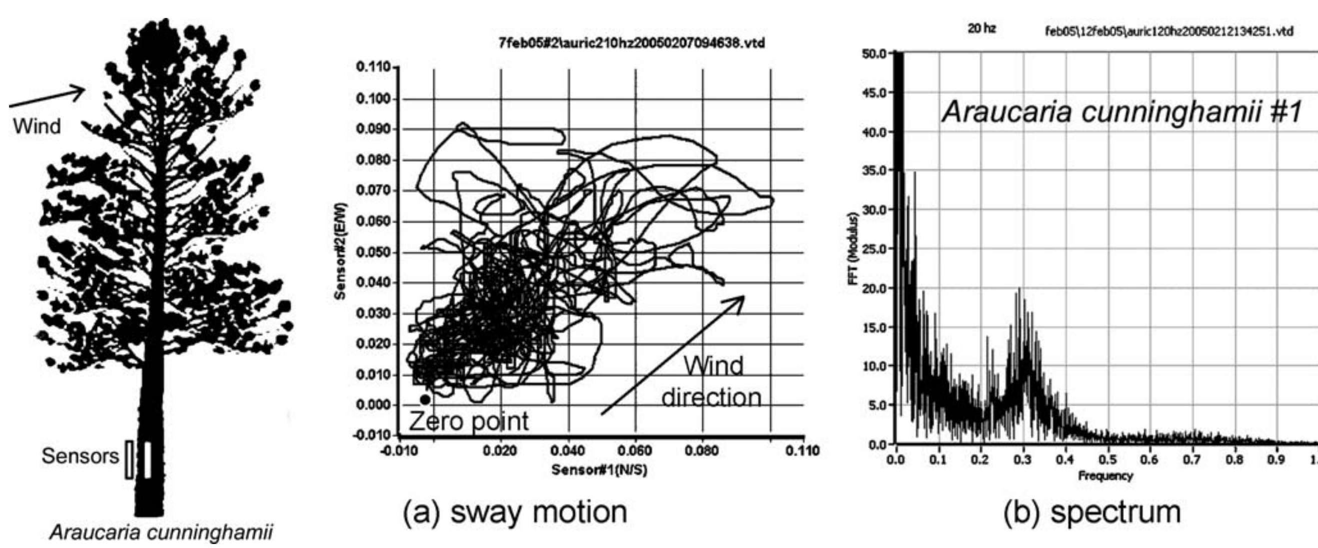

Fig. 7. Sway motion of *Araucaria cunninghamii* (wind speed average 12 m $\cdot$ s^{-1}) showing (a) complex sway motion of tree trunk (down wind only from zero rest point) and (b) spectrum showing sway frequency with single peak at 0.29 Hz.

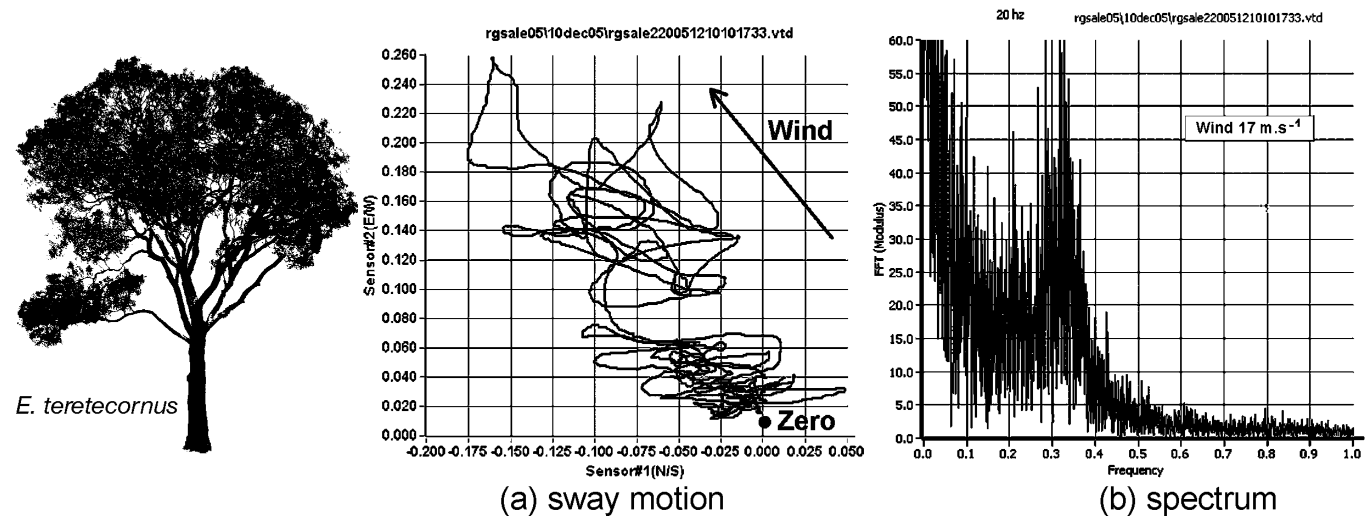

Fig. 8. Sway motion of *Eucalyptus teretecornus* (wind speed average 17 $m \cdot s^{-1}$) showing (a) complex sway motion of tree trunk (down wind only from zero rest point) and (b) spectrum showing sway frequency with broad, single peak at 0.32 Hz.

branch mass to trunk mass increases, the natural frequency of the trunk becomes less dominant. The branches act to dampen or detune the whole structure. This supports the conceptual model presented and indicates that species of trees, with different canopy architecture, may need to be treated differently. How branches, and by implication, branch removal affects trees will need further study. This could influence pruning methods and tree removal techniques so that the mass of branch removal becomes an important consideration, as well as sail area and canopy shape.

The mechanical stability of a tree is its ability to withstand the wind forces that occur throughout its life. Larger trees in exposed areas must endure the largest forces. In many areas, unusual windstorms can generate higher than normal wind speeds, causing failure in trees that would otherwise have survived. The mechanics of failure are influenced by the interaction of tree size and shape, wind speeds, and topography (Stathers et al., 1994).

The wind forces on tree canopies create an overturning moment about the base that is expressed in units of kilonewton meters ($kN \cdot m$). A scale of overturning moments and wind speeds from Cullen (2002) is shown in Fig. 9 to assist interpretation of these numbers.

Calibration tests using ropes have applied static overturning loads up to 60 $kN \cdot m$, which is approximately equal to pulling on a rope with a force of one tonne (1000 kg or 1 ton = 2240 lb) attached at a point 6 m above the base. This is a large value.

Measurements made with the strain meter sensors on trees described earlier, in real wind storms have so far yielded wind loads up to 230 $kN \cdot m$ on 23 m high trees in winds of 22 $m \cdot s^{-1}$ (approx. 50 mph).

Tree failure begins to occur at wind speeds of approximately 25 $m \cdot s^{-1}$ (60 mph) and above (Cullen, 2002; Spatz, 2000). In extreme hurricane events with wind gusts up to 70 $m \cdot s^{-1}$ (150 mph), leaves are stripped from trees and major failure occurs. Tree failure occurred under static pull tests at 300–400 $kN \cdot m$ in tests by Moore (2000), who pulled several hundred mature trees in New Zealand. Some trees broke at the trunk, and some pulled over as the root plate failed in the soil.

These values appear to be upper limits of actual field measurements although other factors such as size, root architecture, and soil type need to be considered. A failure zone is drawn on the scale in Fig. 9a to indicate this limit. Above this failure zone, some calculated values have been presented. Brudi (2002) used a computer-simulated load on a 23 m tree to calculate an overturning moment of 507 $kN \cdot m$.

The highest published value is 1219 $kN \cdot m$ for a 25 m high tree that was assumed to have a wind force of 127 kN acting on

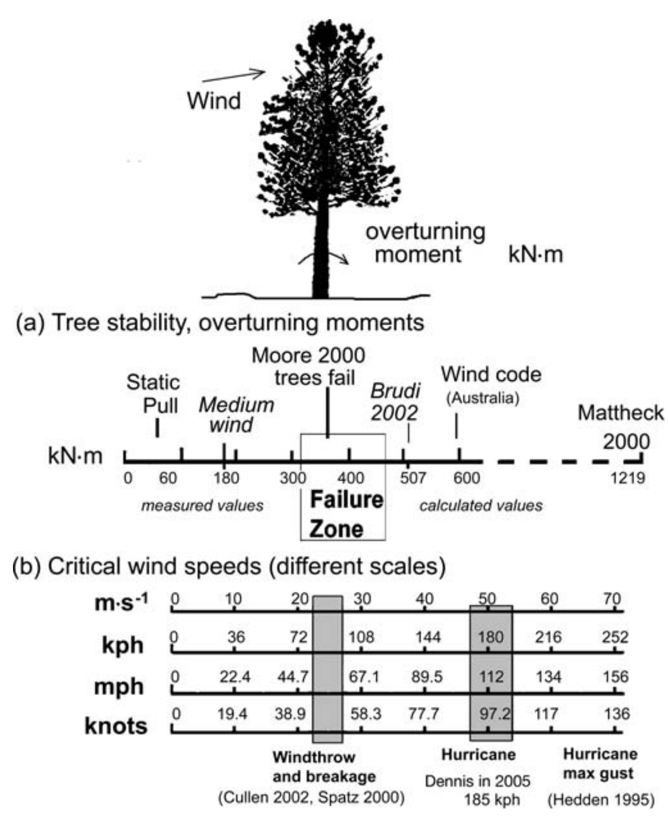

Fig. 9. Tree stability and overturning moments (units $kN \cdot m$). (a) Values from studies, (b) critical wind speeds.

a canopy at 9.6 m height (Mattheck and Bethge, 2000). This calculation was an estimate based on a theoretical analysis of a large tree and the wind forces needed to break the outer fibers of the trunk.

Understanding energy transfer is the key to understanding the complex dynamic response of the tree and its branches in winds. Trees have evolved to grow many branches in a complex three-dimensional architecture that benefits them biologically and physically. The structural advantage is minimization of sway motion and stresses, because of the branch masses dynamically interacting with the main trunk mass. The tree constantly responds to the loads it experiences with two mechanisms, by either growing or shedding limbs. Dynamic balance may be achieved by growth responses, which are very slow, and by suddenly shedding when the wind load is too great for the strength of a branch or limb. In light to medium winds, small outer twigs may be shed so that each branch maintains its detuned structure. In strong winds and storms, large branches or even the main trunk will break, as the tree attempts to survive the extreme conditions.

As a survival strategy, the less energy transferred from the wind to the tree, the better the tree's chance of survival. A larger canopy will catch more wind, and the aerodynamic drag will increase drag forces on the tree. Dynamic mass damping tends to reduce the energy transfer and minimize the occurrence of harmonic or resonant sway frequencies and so detune the structure. The detuning process is a survival strategy that minimizes the transfer of wind energy to the trunk and root system and so results in greater stability.

The initial source of energy is a mass of rapidly moving air (the wind) that applies dynamic loads to the canopy of the tree and causes all the branches, subbranches, and the leaves to move, often with great rapidity. Viscous forces between the air and leaf interface can transfer significant amounts of energy. Vogel (1996) describes storm-resisting features of the design of trees and discusses how structures in nature use flexible survival strategies, whereas human structures and materials are more rigid. Because the energy can neither be created nor destroyed (1st law of thermodynamics), the complex dynamics and interaction of the tree with the wind needs further study to understand the dynamic behavior of tree structures.

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