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A Study of Branch Dynamics on an Open-Grown Tree

Kenneth R. James

Abstract. This study investigates the dynamic properties of branches on an open-grown tree, where most of the mass is in the branches rather than in the trunk. When large branches on open-grown trees sway in winds, they individually and collectively influence how the whole tree sways. If branches are removed, as in pruning, the effect on tree sway has not yet been studied and the literature is almost nonexistent regarding recommendations for pruning open-grown trees to reduce wind damage.

Trees come in many shapes and sizes and in urban areas, usually grow in open spaces and develop many branches. In forests, and particularly in closely spaced plantations, trees grow with an upright central trunk and develop significantly less branch mass.

Forest conifers have been studied to identify their dynamic properties in winds, but the results may be different for open-grown trees. A 19.7 m tall silver maple (*Acer saccharinum*) with four codominant branches was tested by pulling and then releasing each branch to determine the dynamic properties. Branches were progressively removed and the tests repeated. The sway response was recorded with strain instruments attached to the trunk and accelerometers attached to each branch. The dynamic properties of frequency and damping were determined for all tests.

The tree with all branches attached, in full foliage was difficult to sway because of damping from the branches. Significant changes in oscillating frequency and damping were observed only after most of the branches (greater than 80%) were removed. The results support the concept that branches provide damping, which dissipates energy from the wind as a mechanism to help trees survive.

Key Words. *Acer saccharinum*; Branches; Damping; Dynamics; Frequency; Silver Maple.

The aim of this study was to investigate the dynamics of branches on an open-grown tree that had several large branches, meaning that most of the tree's mass was in the branches rather than in the trunk. The idea was to examine how branch removal affects the sway frequency and damping of an open-grown tree. Branch removal (or pruning) may reduce the sail area and exposure to winds, but may also remove the damping of branches. Damping is important because it dissipates energy and so helps reduce large and dangerous oscillations that may be beneficial for trees in high winds. Damping is usually not well understood in vibrating engineering structures (Clough and Penzien 1993). In natural structures, such as trees, damping may be more complex than in man-made structures, and may have a non-linear response that produces soft and hard spring mass systems (Miller 2005). In trees, damping forces are considered velocity dependent (Moore and Maguire 2004; Jonsson et al. 2007); damping is zero when velocity is zero. In static tests, there is no damping present because there is no movement, so dynamic tests must be used to find the amount of damping in a structure.

Trees and branches move in winds and there is significant damping that has not yet been studied in depth. There are many studies, mainly on forest conifers, describing the interaction of wind and trees (Moore and Maguire 2004; de Langre 2008; Gardiner et al. 2008; Sellier et al. 2008), but 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).

Trees come in many shapes and sizes. In urban areas, trees usually develop in an open-grown form, where most of the mass is in the branches and the trunk may be a relatively small proportion of the total mass. In forests or plantations, trees grow closely together and develop fewer and smaller branches so the trunk is the main mass and branches are only a small proportion of the total mass. This difference in how mass is distributed in a tree is very important when the tree and branches move, especially in strong winds and damaging storms. Therefore, understanding the branch dynamics has implications for branch removal and pruning.

The effect of swaying branches on overall tree sway is likely to be different for open-grown trees compared to plantation trees because of the difference in the proportion of branches and the distribution of their mass through the canopy. Previous studies of frequencies and damping on branched and de-branched trees have used plantation trees (Milne 1991; Gardiner 1992; Moore and Maguire 2005). Dynamic tests after progressive pruning of nine plantation-grown Douglas-firs (*Pseudotsuga menziesii*) in the state of Oregon, U.S., resulted in increased natural frequency, but at least 80% of the crown mass needed to be removed before this increase was noticeable (Moore and Maguire 2005). More recent studies on saplings (Sellier and Fourcaud 2009) and open-grown deciduous trees (Kane and James 2011; Ciftci et al. 2013; Kane et al. 2014) have reported on tree frequency and damping, and the data support the importance of crown architecture on predicting dynamic properties, including damping.

METHODS AND MATERIALS

The method described by Moore and Maguire (2005) that progressively removed branches on plantation grown Douglas-firs was used on an open-grown tree that had four main branches and only a small trunk. The testing was done over two days as part of the ISA Biomechanics Week program, in August 2010, and so restrictions of time and equipment limited the scope of the experimental work.

Tree Description

A silver maple (*Acer saccharinum*) with four codominant branches (Figure 1) was selected from a site on a tree research plot of Davey Tree Expert Company, in Shalersville, Ohio, U.S. The tree was 19.7 m tall with a diameter at breast height (DBH) of 0.57 m in the north/south direction and 0.62 m in the east/west direction. The tree trunk was approximately 3 m tall, which then formed into four codominant branches that were approximately of the same diameter and length. The tree was in a full leaf condition.

Testing Schedule

A series of dynamic tests known as pull and release tests (or pluck tests) were conducted on the silver maple by attaching a rope to each branch in turn and pulling then releasing to induce a sway motion. By measuring the sway response after the release point, the dynamic properties of frequency and damping may be determined.

The tests started with all four branches and foliage intact, then one branch was removed and the tests repeated on the remaining three branches. Progressively, one branch was removed and the dynamic tests repeated until only one branch remained. Finally, the last branch was stripped of all foliage and side branches, leaving only a bare branch. This was done to determine the extreme values of damping and frequency, which would be used for comparative or reference data. The testing schedule is shown in Table 1. Branch mass and detailed dimensions were not recorded due to limits of time and equipment.

Figure 1. Silver maple (*Acer saccharinum*) with four codominant branches and strain meter attached to the trunk. Location: Davey Tree reserve, Shalersville, Ohio, U.S. (Note: the fifth smallest branch shown was removed prior to testing).

Table 1. Testing schedule and results of frequency and damping from pull and release test of tree with four branches, initially, and then with branches progressively removed.

Testing Schedule	ω nat freq. (Rad/s)	fo frequency (Hz)	ζ damping ratio (%)
	1. All branches attached		
Branch 1	2.06	0.33	4.5
Branch 2	2.03	0.33	4.0
Branch 3	2.08	0.33	3.5
Branch 4	2.12	0.34	3.5
Trunk (with all branches)	2.12	0.34	10.6
	2. Remove Branch 4		
Three branches remain			
Branch1	1.97–2.06	0.33	6.0–7.4
Branch 2	2.0	0.31	6.0
Branch 3	2.07	0.32	6.0
Trunk (with 3 branches)	2.06	0.33	11.0
	3. Remove Branch 3		
Two branches remain			
Branch1	1.96	0.33	7.5
Branch 2	2.03	0.32	4.0–5.0
Trunk (with 2 branches)	2.02	0.32	11.0
	4. Remove Branch 2		
One branch remains			
Branch 1 with leaves	2.04	0.32	5.0
Branch 1 - bare branch	6.3	1.0	1.3
Trunk (one bare branch)	6.3	1.0	1.1

Instruments

The sway response was recorded with strain instruments attached to the trunk and accelerometers attached to each branch. All data were recorded at 20 Hz, which is sufficient to record the dynamic response of the branches and tree so that the frequency and damping can be accurately calculated.

The strain meter instruments measured the elongation or compression of the outer part of the trunk as it bent during sway movement. Strain is defined as the ratio of the change in length measure in the trunk, divided by the length of the instrument, and, is expressed as a percentage. These instruments have been used to measure dynamic tree response under wind loading (James and Kane 2008; James 2010). For the study, two strain instruments were attached to the trunk of a tree near the base, each oriented in line with the trunk vertical axis and disposed to measure base moments orthogonally, one to the other. The standard method used was to orient one sensor to measure the north/south response and the other to measure the east/west response. The instruments were placed below the lowest branch to ensure that all the dynamic forces from the individual swaying branches above the instruments were recorded.

Each of the four main branches was instrumented with a tri-axial accelerometer (Gulf Coast Data Concepts, model GCDC X6-2), which was used as a tilt meter, with an accuracy of 0.01 degree, and also recorded at 20 Hz. The accelerometer was attached to the branches with two nails and data were stored to memory. After each test, data were downloaded for analysis. The output from the accelerometer was converted to degrees of tilt.

Dynamic Analysis

The analysis of the data from recorded oscillations of each branch and the tree trunk determined the dynamic properties of oscillating frequency (ω_n) and damping (ζ).

For the accelerometer data of the branch sway and the strain meter data of the trunk sway, the time domain data were fitted to a standard equation for a vibrating single degree of freedom (SDOF) mass (Equation 1) (Chopra 1995).

$$[1] \qquad x(t) = ae^{-\omega_n \zeta .t}\left(\cos\left(\omega_d t\right) + \left(\frac{\omega_n \zeta}{\omega_d}\right)\sin\left(\omega_d t\right)\right)$$

where $\omega_d = \omega_n \sqrt{\left(1-\zeta^2\right)}$ and (a) is the initial displacement. Examples of experimental data fitted to the theoretical curve are shown in Figure 2.

A spectral analysis using fast Fourier transformation (FFT) were performed on the strain meter data from the trunk oscillations to examine the dynamic response of the whole tree. The data from one strain meter (x) was used to generate the spectrum *Sx(f)*.

The spectral analysis is used to confirm the oscillating frequency value found from the time domain analysis and also to see if other oscillating frequencies were present.

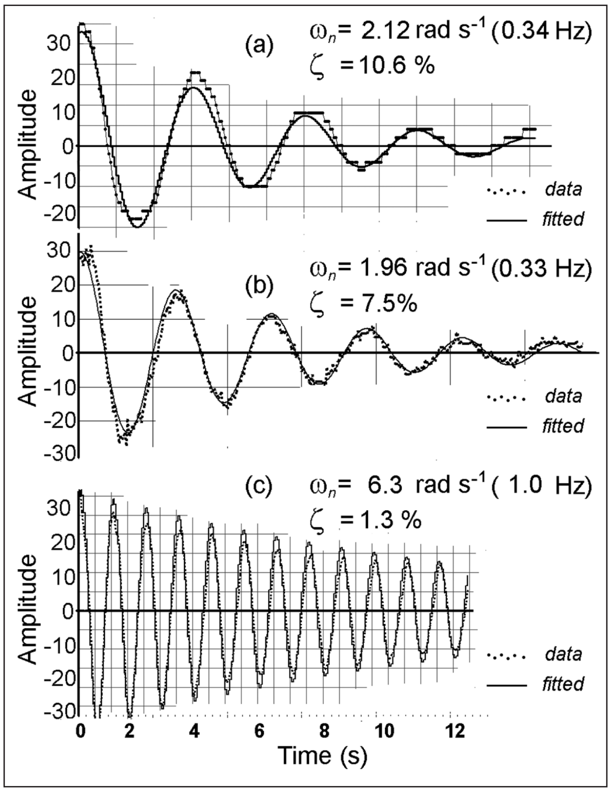


Figure 2. Pull and release test showing damping (ζ) decrease as more branches and leaves are removed. a) Trunk (Test 1) with all branches attached (ζ = 10.6%), b) Branch 1 (Test 3) with one branch removed (ζ = 7.5%), and c) Branch 1 (bare) with all leaves removed (Test 4) (ζ = 1.3%). Data were fitted to theoretical curve to determine frequency (ϖ_n) and damping ratio (ζ).

RESULTS AND DISCUSSION

The results for all tests are shown in Table 1. The accelerometer data was used for the branches and the strain meter data used for the trunk. Test 2 removed one branch, Test 3 removed a second branch, and Test 4 had only one branch left attached to the trunk.

Results from some pull and release tests are shown for three different levels of damping in Figure 2. The trunk damping, when all branches are attached, was ζ =10.6% at a natural frequency of 0.34 Hz (Figure 2a). This value was found as each branch was individually pulled, then released, and the resulting motion transferred to the trunk and also to the other branches. The damping on Branch 1 after two branches were removed (Test 3, Branch 1) shows ζ = 7.5%, which is higher than in previous tests because the amplitude was larger (Figure 2b). This happened because the field technicians became more confident and applied a greater force at each test. In a pull and release test, the changing amplitudes will result in different values for damping ratios as the velocity through the air increases. The damping on Branch 1, after all branches were removed, and all the leaves on Branch 1 were also removed (Test 3, Branch 1), shows ζ = 1.3% (Figure 2c).

A high damping ratio of 10% will indicate a high level of energy dissipation, and after the release, only four oscillations will occur before the mass returns to its rest position (Figure 2a). A low damping ratio of 1% will mean much less energy is dissipated and the oscillations will continue for a much longer time (Figure 2c).

A spectral analysis was performed on the strain meter data from the trunk (Figure 3) for each of the tests when the tree had four, three, two, and then one branch.

In Test 1, with four branches attached, the sway frequency of the trunk and all four branches can be considered as the same at 0.33 Hz (Table 1; Figure 3a), which is within the accuracy of the experimental method. The damping was similar between the branches (3.5% to 4.5%) and was significantly less than the trunk damping response at 10.6%.

The damping ratio of each branch varied depending on how the pull and release test was performed, with higher values of damping ratio occurring when large sway amplitudes were induced. Values of 4.5% (low amplitudes) to 7.5% (high amplitudes) could be generated for Branch 1. Damping is generally assumed to be amplitude dependent (Clough and Penzien 1993). If large sway amplitudes were developed during a test, there was likely to be a larger relative velocity between the air and the branch, and consequently a larger aerodynamic drag component. After some initial trials, the pull and release of the branches was made as uniform as possible between branches and between tests. There are obvious limits to the accuracy of

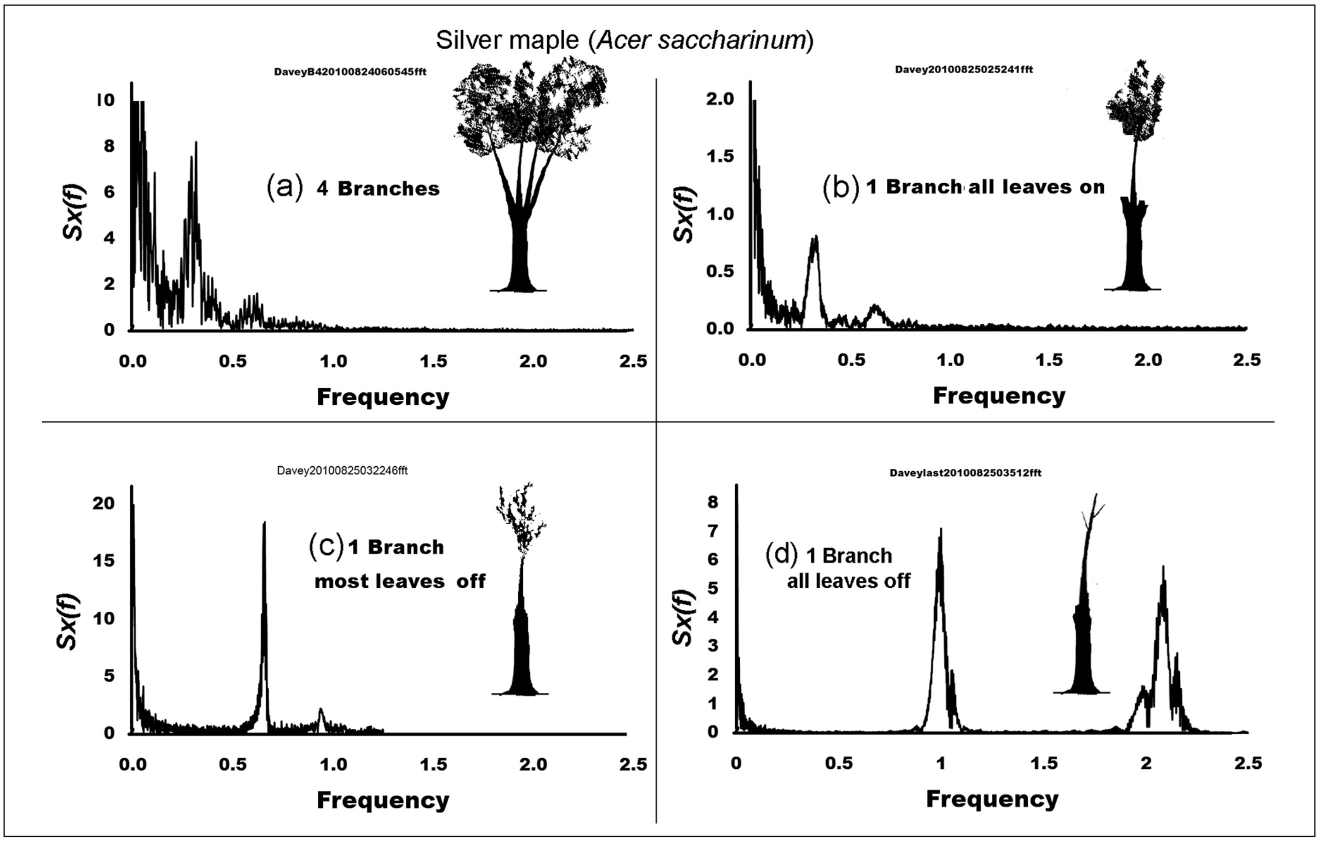


Figure 3. Trunk sway spectra showing frequency response from pull and release tests with a) four branches; b) one branch, leaves on; c) one branch; most leaves off; and d) one branch, all leaves and small branches removed.

the damping values quoted but any large difference should still be apparent from these tests.

One branch was removed for Test 2 and the remaining three branches were swayed. Individual branches had similar frequency of oscillation and damping ratios were slightly larger (6.0% to 7.4%) than Test 1. The trunk sway frequency and damping were similar to Test 1. In Test 3, the tree had two remaining branches, and the frequencies and damping of the branches and trunk were similar to the previous two tests.

In Test 4, only one branch with foliage remained for the sway test and the results were again similar to the previous tests. This was unexpected because it was thought that a significant change would be found in the measured frequency and damping ratio after approximately 75% of the canopy was removed. It was then decided to remove all the foliage and all the side branches from the last branch for the final test.

The data for the bare branch suggests significant change in frequency and damping. The frequency increased from 0.33 Hz to 1.0 Hz and the damping ratio of both the branch and the trunk reduced from 5% to approximately 1.0%. From observation, the bare branch swayed much more than for all other tests. By changing the pulling frequency of the rope, it was possible to induce a second mode of sway with a frequency of 2 Hz, which shows as a second peak in Figure 3d. It was not possible to induce this modal response in any of the other tests.

Energy Transfer

In the pull and release test, the mass is deflected and held in position and upon release, the stored energy is released and causes the branch to oscillate. As a first approximation, a tree or an individual branch may be considered as a single oscillating mass (Figure 4a) that may be studied as a model (Figure 4b) that has a mass (m), which when deflected, stores energy like a spring (k), and after release the oscillation displacement (x) gradually goes to zero as the energy is dissipated in a damper (c). This model with one mass is known as a single degree of freedom system because it has a single oscillating response.

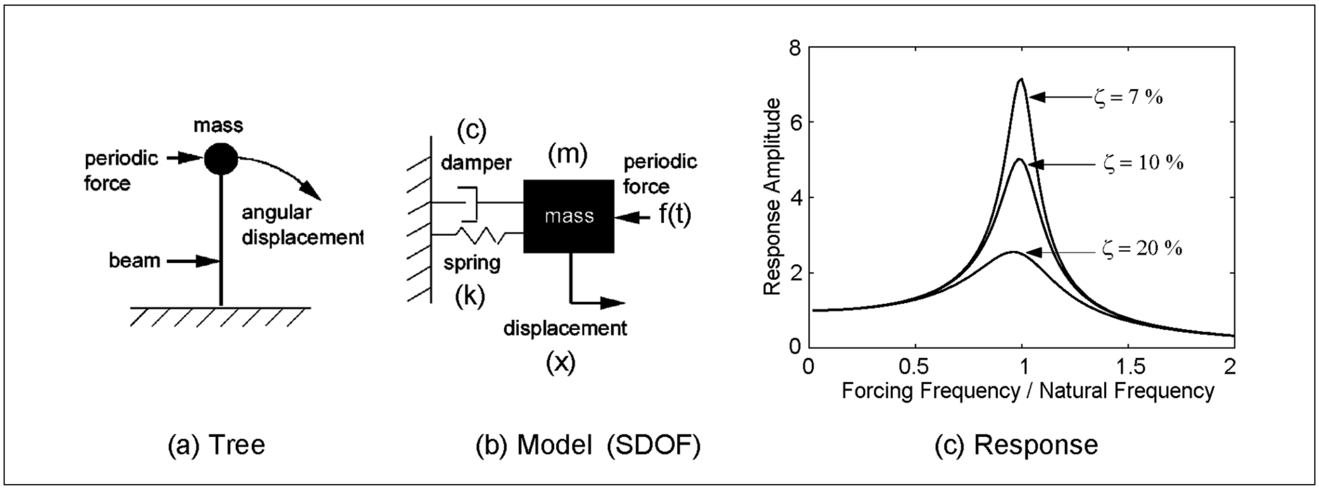


Figure 4. A simple tree dynamic model with a single oscillating mass, known as a single degree of freedom model. a) Simple tree model; b) an equivalent dynamic model with mass (m), damper (c), and spring (k); and c) sway amplitude response varies with damping (Miller 2005).

The pull and release test is an artificial test and is different from energy transfer in wind that causes the tree to sway with the trunk and the branches to move as masses linked together. In a pull and release test there is no periodic force applied to the mass [i.e., f(t) = 0]. In winds, the periodic force f(t) pushes on the tree at a range of frequencies (the forcing frequency), and when this corresponds to the natural frequency of the mass, the response amplitude can increase substantially if there is little (or no) damping. This is shown in Figure 4c (Miller 2005) where the x axis is the ratio of forcing frequency divided by the natural frequency and the point of resonance is when this ratio is one. The response amplitude is high when the damping is low (7%) because the input force comes in time to help the mass sway, and there is not much dissipation of energy to keep the sway response low. When the damping is high (20%), the response amplitude is low because the energy is dissipated and large sways are not possible.

The simple dynamic SDOF approach has been applied to trees (Milne 1991; Baker and Bell 1992; Flesch and Wilson 1999; Miller 2005; Jonsson et al. 2007). The energy dissipation or damping is considered to have several components, including aerodynamic drag, internal energy loss as the tree bends, energy loss in the soil root plate system, and possibly crown collisions when two nearby trees collide (Milne 1991).

How Branches Affect the Dynamic Response

Branches are masses that are attached to the trunk and oscillate partly as individuals and partly as components of the whole tree. The branch masses may be referred to as coupled masses that are not fully independent of the main trunk, yet have their own sway response. Branches also have sub-branches that further act as coupled masses on the larger branch (Figure 5a). The mass of the trunk, the branches, and the sub-branches may be modeled as a multi-mass, spring, damper system (Figure 5b), and the many coupled masses will oscillate so that a multi-degree of freedom (MDOF) response occurs. It is only when two or more coupled masses oscillate that another form of damping, termed mass damping (James et al. 2006) or structural damping (Spatz et al. 2007), can occur, which reduces the response amplitude (Figure 5c).

Previous dynamic studies of trees (Mayhead 1973; Mayhead et al. 1975; Milne 1991; Roodbaraky et al. 1994; Baker 1997; Hassinen et al. 1998; Flesch and Wilson 1999; Moore and Maguire 2004; Jonsson et al. 2007; Spatz et al. 2007; Kane and James 2011; Rodriguez et al. 2012) established natural sway frequencies and damping ratios, at times finding that branches should be considered as individual damped oscillators rather than masses rigidly attached to the trunk (Moore and Maguire 2005).

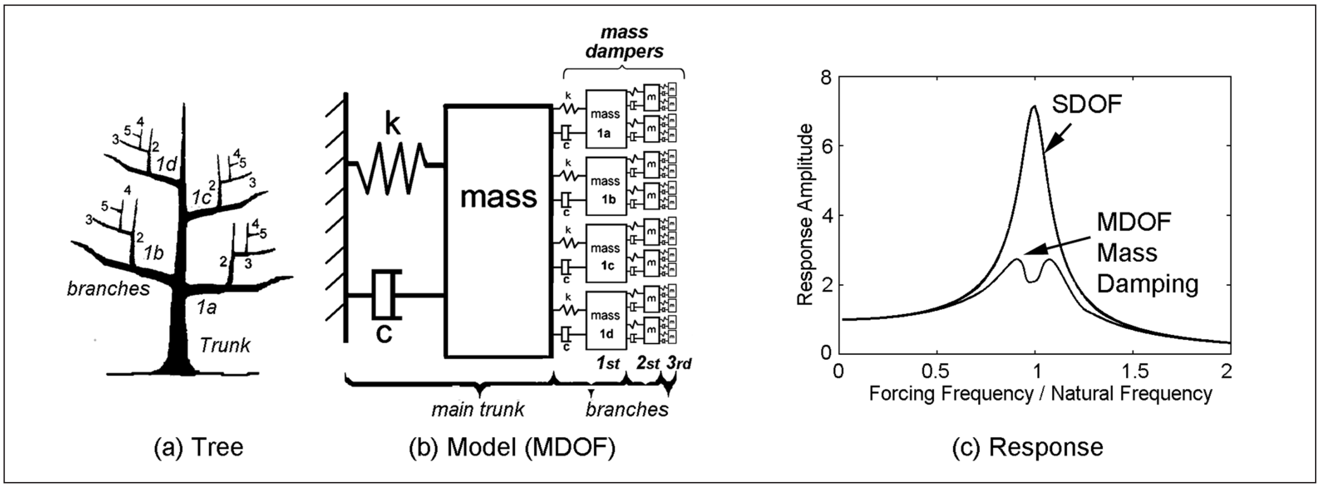
Tree shape and branch mass distribution influence the dynamic sway responses, and recent studies using a MDOF approach are finding that the form and shape of a tree is important when studying tree dynamics (de Langre 2008; Rodriguez et al. 2008; Sellier and Fourcaud 2009; Thekes et al. 2011; Spatz and Thekes 2013). Damping by branching is proposed by Thekes et al. (2011) as a new damping mechanism inspired by the architecture of trees (Figure 6).

CONCLUDING REMARKS

These tests showed that branches in full foliage have high damping, and that open-grown trees with many branches will have a very high overall level of damping. Although no mass measurements were made of the branches removed, it is estimated that considerably more than 80% removal, as found by Moore and Maguire (2005), was needed to cause significant changes in oscillating frequency and damping.

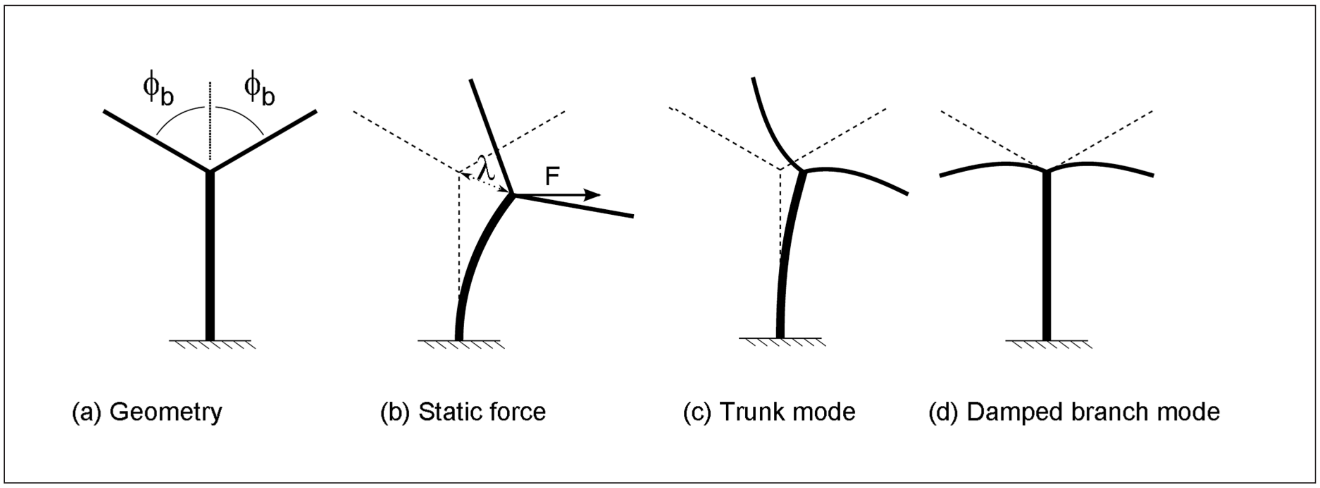
This study was limited to a simple evaluation of the damping and frequencies for this tree and provides useful insight into the topic of damping in trees, rather than proving or disproving a scientific theory. No attempt has been made to identify the components of damping but the results support the idea that for an open-grown tree with large branches, a high level of damping is present.

Damping dissipates energy (Spatz and Thekes 2013) and may be an important factor in helping trees to survive winds. The influence of the crown structure (Ciftci et al. 2013; Kane et al. 2014) and small morphological varia-



(a) Tree (b) Model (MDOF) (c) Response

Figure 5. Complex tree dynamic model with a) branches included as coupled masses; b) multi-mass model with individual mass (m), spring (k), and damper (c) for each trunk and branch; and c) a MDOF response with mass damping.



(a) Geometry (b) Static force (c) Trunk mode (d) Damped branch mode

Figure 6. Damping by branching (Thekes et al. 2011). a) Geometry of two branch model with branch angle (ϕ_b); b) static initial conditions with applied force (F) and deflection (λ); c) trunk mode sway response; and d) damped branch mode.

tions in a tree's crown, due to branch architecture (Sellier and Fourcaud 2009), may be very significant in the dynamic response of trees.

Further work is needed to fully understand the dynamic role of branches, particularly for recommendations for the pruning of open-grown trees.

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Zusammenfassung. Diese Studie untersucht die dynamischen Eigenschaften von Ästen an einem offenkronigen Baum, wo die größte Masse eher in den Ästen als in Stamm steckt. Wenn große Äste eines offenkronigen Baumes im Wind schwingen, beeinflussen sie damit individuell und kollektiv die Schwingung des ganzen Baumes. Wenn Äste entfernt wurden, wie beim Kronenschnitt, wurden die Auswirkungen auf die Baumschwingung bislang noch nicht wissenschaftlich untersucht und es gibt so gut wie keine Literatur mit Empfehlungen zum Schnitt von offenkronigen Bäumen, um Windbruch zu reduzieren.

In urbanen Räumen kommen Bäume in allen Formen und Größen vor, wachsen gewöhnlich in offenen Flächen und entwickeln viele Äste.

Ein 19,7 m hoher Silberahorn mit vier Hauptästen wurde zunächst gezogen und dann entspannt, um die dynamischen Eigenschaften dabei zu testen. Anschließend wurden progressiv Äste entfernt und der Test wiederholt. Es wurden Dehnungsinstrumente am Stamm und Geschwindigkeitsmessinstrumente an jedem Ast befestigt und die im Test entstehende Schwingung aufgezeichnet. Für jeden Test wurden die dynamischen Eigenschaften von der Frequenz und Schwingungsdämpfung bestimmt.

Der Baum, mit all seinen Ästen angeschlossen und voller Belaubung, war schwierig zu schwingen, weil die Äste ihn abdämpften. Aber erst nach dem Entfernen von mehr als 80 % der Äste konnten signifikante Änderungen der Frequenzen und Dämpfungen beobachtet werden. Diese Ergebnisse unterstützen das Konzept, dass die Äste eine Schwingungsdämpfung leisten, indem sie die Windenergie reduzieren, dass es ein baumeigener Mechanismus zum Überleben von Windereignissen ist.

Resumen. Se investigan las propiedades dinámicas de las ramas de un árbol en un área abierta, donde la mayor parte de la masa está en las ramas y no en el tronco. Cuando las ramas grandes de los árboles que crecen a campo abierto se mecen con los vientos, éstos influyen individual y colectivamente en la forma como se mecen los árboles. Si se quitan las ramas, como en la poda, el efecto sobre la influencia en el árbol aún no ha sido estudiado y la literatura es casi inexistente respecto a las recomendaciones para la poda de árboles a campo abierto para reducir los daños del viento. Los árboles son de muchas formas y tamaños y en las zonas urbanas por lo general crecen en áreas abiertas y desarrollan muchas ramas. Los bosques de coníferas han sido estudiados para determinar sus propiedades dinámicas en los vientos, pero los resultados pueden ser diferentes para los árboles que crecen a campo abierto. Un maple plateado de 19,7 m de altura (*Acer saccharinum*) con cuatro ramas principales se probó tirando y liberando de cada rama para determinar las propiedades dinámicas. Las ramas fueron eliminadas progresivamente y las pruebas se repitieron. La respuesta fue grabada con instrumentos de resistencia unidos al tronco y acelerómetros unidos a cada rama. Las propiedades dinámicas de frecuencia y amortiguamiento se determinaron para todas las pruebas. El árbol con todas las ramas en todo el follaje era difícil de mecer debido a la amortiguación de las ramas. Se observaron cambios significativos en la frecuencia de oscilación y amortiguamiento sólo después que la mayoría de las ramas (superior al 80 %) fueron retiradas. Los resultados apoyan el concepto de que las ramas proporcionan amortiguación que disipa la energía del viento lo cual es un mecanismo para ayudar a los árboles a sobrevivir a los vientos.

APPENDIX.
LIST OF SYMBOLS.

$x(t)$	amplitude (varies with time)
a	the initial amplitude
ω_n	natural frequency (radian/s)
ω_d	frequency of damped mass (radian/s)
t	time (s)
ζ	damping ratio (%)
f	frequency (Hz)
$Sx(f)$	spectrum of data from x amplitude