Branches and damping on trees in winds

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BRANCHES AND DAMPING ON TREES IN WINDS

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ABSTRACT

Understanding how natural structures such as trees survive extreme loading in nature may help develop new ideas that have application in the design of man-made structures. Natural structures like trees repeatedly endure large dynamic loads from winds and in most cases survive with little or no damage. Recent studies of trees using complex models and multi-modal analysis have indicated that the morphology of a tree and the dynamic interaction of branches can influence the damping response in winds. Branches on trees act as coupled masses and in winds develop a mass damping effect which helps distribute, reduce and dissipate the wind energy. The dynamic properties of trees and the damping effect of branches obtained from field tests are presented. The results are discussed with a view to using some principles of how slender and flexible structures survive extreme loading in nature, and applying these to the design of man-made structures.

KEYWORDS

Damping, flexible, branches, trees, dynamics, wind.

INTRODUCTION

Dynamic loads on structures and vibrations from external excitations such as wind and earthquakes is an important issue in mechanical engineering (Den Hartog 2007) and understanding how natural structures such as trees survive in winds may provide new ideas that have application in the design of man-made structures. New disciplines such as bioinspiration or biomimetics are investigating biological and natural systems to develop new concepts in vibrations problems such as shock absorbing devices (Yoon and Park 2011).

Studies of tree dynamic response using complex models and multi-modal analysis indicate that the morphology of a tree and the dynamic interaction of branches can influence the damping response in winds (Rodriguez et al. 2008). Small morphological variations can produce extreme behaviours, such as either very little or nearly critical dissipation of stem oscillations and the effects of branch geometry on dynamic amplification are substantial yet not linear.

Tuned mass dampers (TMD) are used to reduce wind induced vibrations in tall buildings such as Citicorp (New York) and Taipei 101 in Taiwan (Aly 2014). A TMD consists of a spring mass damper system connected to the main structure but new concepts incorporate multiple TMDs as part of the structure in floors that aid in vibration control without adding any extra mass to the structure (Xiang and Nishitani 2014). In trees, branches act as coupled oscillators or as multiple mass dampers (James et al. 2006) and provide damping by branching (Thekes et al. 2011).
This paper describes the dynamic properties of trees and the role of branches that act as tuned mass dampers to provide damping in winds. The results are presented and discussed to show how trees dissipate wind energy and may offer some design concepts useful for buildings and other structures.

**METHOD OF SOLUTION**

The dynamic response of trees in high winds has been recorded using (a) strain meter instruments attached to the main trunk and (b) accelerometers acting as tilt sensors that attach to the base of the trunk at ground level. Standard cup-cone anemometers have been used to measure incident wind.

The strain meter instruments measure the outer fibre elongation of the trunk as it bends and two strain instruments are attached orthogonally on the trunk to measure the north/south response and the other to measure the east/west response. The instruments are placed below the lowest branch to ensure that all the dynamic forces from the individual swaying branches above the instruments were recorded. All data are recorded at 20 Hz so that the dynamic response of trees at approximately 0.1 to 1.0 Hz is captured. This sampling rate is sufficient to calculate spectra using fast Fourier transformations.

By using a static pull test, the strain data may be calibrated to determine bending moments at the tree base, which can then be used as a measure of wind loading (James et al. 2006). Pull and release tests (or pluck tests) are also used to evaluate the damping of trees and branches in still air conditions. (James 2014).

**Spectral Based Model for Wind Loading on Trees**

The dynamic character of the response of trees to wind, lends itself to a spectral modelling approach. A brief overview is provided here of the approach. Details can be found in James & Haritos (2008). Consider an equivalent single degree of freedom (SDOF) modelling of the displacement response to wind excitation of an urban tree, taken at the centroid of exposed area of the tree canopy, given by \( x(t) \), then:

\[
m\ddot{x} + c\dot{x} + kx = F(t)
\]  

(1)

in which \( m \) is the equivalent mass, \( c \) the equivalent structural damping and \( k \) the equivalent stiffness, at the centroid of exposed area of the tree canopy.

The in-line wind force, \( F(t) \), acting on a tree is considered to be drag dependent, so would be related to the relative along wind speed, \( (V(t) - \dot{x}(t)) \), where \( V(t) \) and \( \dot{x}(t) \) are the wind speed and tree velocity, respectively.

Because tree canopies tend to be dominated by leaves and twigs that deform and “streamline” in the wind, a wind speed dependent \( \alpha \) value is introduced for canopy wind force, viz

\[
\alpha = \alpha_o \left( \frac{\bar{V}^n}{\bar{V}^2} \right) = \alpha_o \bar{V}^{n-2}
\]  

(2)

\[
F(t) = \alpha_o \bar{V}^{n-2} (V(t) - \dot{x}(t))^2 \left( \alpha_o = \frac{1}{2} \rho C_{Do} A_o \right)
\]  

(3)

in which \( \rho \) is air density (~1.2 kg/m\(^3\)), \( C_{Do} \) is the total effective drag coefficient for the tree, branches and leaves and \( A_o \) is the orthogonal area of exposure to the wind of these elements, both under still wind conditions, respectively. The exponent \( n \) is less than 2.

For \( F(t) \) acting at a height above the ground of \( h_m \), corresponding to the centroid of the exposed area to wind of the tree, the base moment acting on the tree trunk, is given by:

\[
M(t) = h_m F(t) = \beta V^2(t) \quad (\beta = h_m \alpha)
\]  

(4)

Simply multiplying both sides of Eqn. (1) by \( h_m \), we have:
\[ h_m \left( m\ddot{x}(t) + c\dot{x}(t) + kx(t) \right) = h_m F(t) = M(t) \]  

(5)

Now for along wind speed consisting of a mean, \( \bar{V} \), and turbulent component, \( v(t) \), then

\[ V(t) = \bar{V} + v(t) = \sqrt{1 + \frac{v(t)^2}{\bar{V}}} \]

(6)

After considering Eqn. (2), the base moment of the tree is therefore given by:

\[ M(t) = \beta \bar{V}^2 \left[ 1 + \left( \frac{v(t)}{\bar{V}} \right)^2 + 2 \left( \frac{v(t)}{\bar{V}} \right) \right] - 2 \beta \bar{V} \dot{x}(t) \]

\[ = \bar{M} + m(t) - h_m c_a \dot{x}(t) \]

(7)

in which \( \bar{M} = \beta \bar{V}^2 \left( 1 + I^2 \right) \); \( m(t) = 2 \beta \bar{V} v(t) \); \( c_a = 2 \alpha \bar{V} \); \( I \) is the turbulence intensity, \( v_{RMS} / \bar{V} \).

The assumption made here is that both the response \( \dot{x}(t) \) and the wind speed fluctuation \( v(t) \) are small compared to the mean wind speed, \( \bar{V} \). The term \( c_a \) in Eqn. (7) can be considered to be an “aerodynamic damping” contribution term and can be taken to the left hand side of Eqn. (5) to enhance the overall damping, so that:

\[ h_m \left( m\ddot{x}(t) + (c + c_a)\dot{x}(t) + kx(t) \right) = \bar{M} + 2 \beta \bar{V} v(t) \]

(8)

Considering the above modelling approach, the spectral description for the base bending moment of a tree under wind excitation, \( S_m(f) \), can therefore be obtained by considering fluctuating terms, viz:

\[ S_M(f) = \left( 2 \beta \bar{V} \right)^2 \chi_m^2(f) \chi_a^2(f) S_v(f) = T^2(f) S_v(f) \]

(9)

in which \( \chi_m^2(f) \) is the structure magnification function, \( \chi_a^2(f) \) is the “aerodynamic admittance” function – a tree size dependent/frequency dependent reduction factor, \( S_v(f) \) is the along wind speed spectrum, and \( T^2(f) \) represents the overall transfer function given by:

\[ \chi_m^2(f) = \frac{1}{1 - \left( \frac{f}{f_o} \right)^2 + 2 \zeta \left( \frac{f}{f_o} \right)^2} \]

\[ T^2(f) = \left( 2 \beta \bar{V} \right)^2 \chi_m^2(f) \chi_a^2(f) \]

(10)

(11)

where \( \zeta \) represents the effective damping ratio (inclusive of all damping contributions) and \( f_o \) the primary mode frequency of the tree. The above modeling approach can be further refined by introducing the concept of modal response fixed at the primary mode shape, \( \phi(z) \), with amplitude \( \eta(t) \) at the reference point – the effect of which is considered to be small in the case of typical tree structural forms.

**RESULTS AND DISCUSSIONS**

The dynamic response measurements of over 300 trees in high wind conditions have been recorded in urban areas and Eqn (11) has been applied to the data to determine overall damping realised in tree structures. Only some representative samples of the data are presented here. Trees with significantly different canopy shapes and therefore different “structural” characteristics demonstrate the applicability of the spectral based approach (Figure 1), despite the limitations associated with the single degree of freedom (SDOF) modelling assumption associated with Eqn (1).
The dynamic response of an Italian cypress (*Cupressus sempervirens*) (Figure 1a) has a flexible response and acts like a pole or cantilever beam with a 1st and 2nd mode showing in the spectrum. The primary mode of vibration is associated with a narrow response peak (reasonably low overall damping) and a secondary peak associated with the second cantilever mode of vibration.

A tree with many large branches, a Red gum (*Eucalyptus tereticornis*) has a strongly damped response (Figure 1b) due to branches that act as oscillators on the main trunk, each with their own natural frequency that appear to be closely spaced so that a significant mass damping effect occurs reducing otherwise large maxima. Figure 1 spectra use approximately 23 minutes of data sampled at 20 Hz.

Figure 2. Time domain data of X and Y axes over 20 min showing looping motion of tree and along wind and across wind motion.

The same data in the time domain is shown for the Red gum (Figure 2) of the base moment (kNm) over a 20 minute time period. The along wind and across wind response has been converted to base...
bending moment which is the overall trunk response caused by the many swaying branches which oscillate at their own frequencies in a complex in-phase and out-of-phase relationship with the trunk motion.

The complex response can be viewed as a multi-modal behaviour with a suggested model (Figure 3) representing a multi spring-mass-damper system. Application of SDOF model fitting for damping value (via model of Eqn 11) to Red Gum 1 leads to similar “primary mode” frequencies in trees of this type in the approx. range 0.2 to 0.4 Hz (Figure 1b), not unlike the result for the Italian Cypress first mode frequency (Figure 1a).

**Damping**

In classical vibrations analyses, four common types of damping mechanisms are used to model vibratory systems (Balachandran and Magrab 2004) as (i) viscous damping; (ii) Coulomb or dry friction damping; (iii) material or solid or hysteretic damping, and (iv) fluid damping. In all these cases, the damping force is usually expressed as a function of velocity and may be grouped together to give one value for overall damping which in tree studies is usually assumed to be viscous damping (Moore and Maguire 2004).

Another type of damping is described by Den Hartog (1956) as a dynamic vibration absorber or as a mass damper. The dynamic vibration absorber is a device which consists of two oscillating masses; one coupled to the other via a system of springs and may be incorporated into a structure as a device which will transfer some of the structural vibrational energy from the primary structure to the tuned mass damper, thereby introducing a “damping effect” by reducing the peak response of the system.

![Figure 3. Model of a tree, showing the primary oscillating mass of the trunk and the attached branches acting as coupled oscillators that develop a multi-tuned mass damper effect (James et al. 2006).](image)

The energy loss mechanisms associated with damping in trees are not fully understood (Moore and Maguire 2004). In this study the highest damping was observed in the red gum (16%) and the lowest value of damping was in the Italian cypress (8%). On plantation grown trees, with few branches, the damping ratio values from pluck tests range from 1.2% on Sitka spruce to 15.4% on Douglas fir (Moore and Maguire 2004). Values varied considerably between individual trees and between species with no clear relationship. The method described by Moore and Maguire (2004) using pluck tests was exercised on a tree with several large branches to record damping ratios of 10.6% when the tree had all branches attached. As branches were progressively removed the damping ratio decreased until the lowest damping of 1.3% was recorded when only one bare branch was left (Figure 4).
Figure 4. Damping values of a Silver maple tree (Acer saccharinum) determined from pluck tests with (a) 4 main branches and foliage attached (ζ = 10.6%), (b) two branches on after two branches removed (ζ = 7.5%), and (c) one branch (bare) with all leaves removed (ζ = 1.3%) (James 2014).

CONCLUSIONS

The dynamic response of trees is complex due to the dynamic interaction of branches acting as multiple mass dampers. The overall damping is also complex and depends, amongst other things, on the tree architecture and distribution of mass throughout the tree canopy. Understanding how trees survive in high winds and the complex damping mechanisms associated with them may assist with design concepts applicable to man-made structures.

REFERENCES