Tree Cable Loads During High Winds:
Part 1 - Effects of wind excitation

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1. INTRODUCTION

Steel cables are often used to support tree limbs in an attempt to minimise the risk of tree failure in urban areas of Australia. During high winds, cables undergo severe loading, often to the point of failure, yet there is little information on the actual loads encountered. The dangers of trees and branches failing in urban areas is a cause of great concern to arborists due to the potential for damage to people and property, and the increasing likelihood of litigation and liability claims. The present guidelines for cabling and bracing are those of the American National Arborist Association [9]. Whilst this guide indicates the size of the steel cable to be used on a limb of a specified diameter, there is no accurate information on specific loads encountered. It is important that some estimate of the tree cable loads be established so that guesswork can be reduced and the arborist has more precise guidelines regarding tree cable selection and installation.

Part 1 of this paper describes the problem of supporting trees using steel cables and the effect of wind on tree structures. Modelling of the dynamic response (mechanical) of a tree to wind excitation is also discussed. Part 2 describes the equipment and methods developed to monitor time varying loads in tree cables during wind storm events and presents some experimental results from field trials and preliminary analyses leading to further work.

2. TREE RESPONSE TO CABLE INSERTION AND MECHANICAL STRESS

The use of cables in a tree structure changes the stress distribution and loading on tree limbs. The cables are used to support limbs but in doing so, restrict their movement and change the dynamic loading within a tree structure. This may result in a desirable reduction in stress on a limb or a crotch, but may also cause unwanted increases in stress at other locations such as where cables are attached to limbs.

Trees respond to mechanical stress by growing thicker at points of high stress in order to relieve the stress loading. Mattheck [6] discusses a "constant stress hypothesis" which proposes that tree growth is in response to mechanical stress. "No point on a tree surface has to carry more load than any other point." If surface stresses are high at one point, a tree will thicken or grow to relieve this stress. This thickening at stress points is observed at points of cable attachment and has been reported in experiments by Jacobs in Australia in 1935 [8].

Tree growth in response to mechanical stress is illustrated by trees growing in windy sites which have thicker trunks than those growing in still conditions. The tree responds by producing additional growth at points of high mechanical stress termed"reaction wood". There are two types of reaction wood (ie compression or tension reaction wood) depending on the type of tree. Conifers add compressive reaction wood and broadleaved species add tension reaction wood [2, 3, 7]. The compression reaction wood of conifers and the tension reaction wood of broadleaved tress display different physical and structural characteristics, [3,5]. Compression reaction wood in conifers occurs on the underside of branches and the leeward side of trunks. Tension wood in broadleaved trees occurs on the upper side of branches and on the windward side of the trunk.

The long term effect on a tree, of inserting a cable, can therefore greatly change the future performance of that tree. Whilst a cable may provide some short term support of a limb, the altered stress state on the tree structure may stimulate reaction wood to form which in the long term completely alters the way the tree responds to wind loading. Consequently, the loads that are eventually developed in the tree structure that has thickened due to cable insertion, may be greater than if the cable were not present. In the longer term the cable may in fact weaken rather than strengthen the tree structure.

3. THE EFFECT OF WINDS ON TREE STRUCTURES

Wind comes in periodic gusts which set up a sway motion of the limbs and produces a dynamic excitation of the tree structure. This may result in forces up to three times greater than for a constant wind and will result in a sway motion with a natural period of 2 to 3 seconds for a 15 metre high, single stem conifer [8]. Milne [8] reports that there is no quantitative data correlating the frequency of wind gusts with the corresponding dynamic sway motion of a tree. Tree sway periods of between 1.5s and 5s are reported, with values depending on tree height, centre of gravity, trunk diameter, trunk taper, wood density and elasticity, etc., although the relative weight of each has not yet been quantified, [1].

The effect of wind and movement on tree growth can be considerable, with reports of trees growing in still air being up to 30% taller than those grown in windy conditions [3]. Trees have evolved to suit different biological and physical conditions and to respond to wind induced stress by strengthening trunks and limbs in the appropriate areas by adding reaction wood.

4. MODELLING DYNAMIC EXCITATION FROM WIND

Structurally, trees consist of a complex assemblage of beam elements. A first attempt to model the dynamic response of a tree, (with or without cable elements), due to the forcing action of turbulent wind can be made using Finite Element Method (FEM) modelling techniques which produce the classical set of second order differential equations given by:

$$\mathbf{m}\ddot{y} + \mathbf{c}\dot{y} + \mathbf{k}y = f \qquad (1)$$

where **m**, **c**, and **k** represent symmetric matrices for the mass, damping and stiffness ; $y, \dot{y}, \ddot{y}$ represent the time varying vertical displacement, velocity and acceleration vectors and f the vector of the time varying wind force at discrete locations adopted in the model.

While it is relatively easy to establish **m**, and **k** using widely available FEM modelling software, the practical solution of eqn. (1) using such software can only be realised in the situation of linear elastic material behaviour and proportional damping, ie damping matrix, $\mathbf{c} \approx \alpha\mathbf{k} + \beta\mathbf{m}$, (where α and β are constant factors). It then becomes possible to uncouple this set of simultaneous second order differential equations to produce:

$$\ddot{a} + \mathbf{diag}2\omega_n\zeta_n\dot{a} + \Lambda a = \Phi^T f \qquad (2)$$

where the substitution $y = \Phi a$ has been made in which Φ represents a matrix whose columns are composed of the individual undamped or "natural" mode shapes, ϕ_n, (solutions to $(\mathbf{k} - \omega_n{}^2\mathbf{m})\,\phi_n = 0$); $a, \dot{a}, \ddot{a}$, represent vectors of modal amplitudes, velocities and accelerations respectively and ω_n and ζ_n, represent the associated natural circular frequency (where $\omega_n = 2\pi f_n$) and damping value (ratio to critical) of mode "n", [4].

Unlike man-made structures (such as towers, tall buildings, bridges, etc), trees do not exhibit modes that are well separated in frequency so that their response cannot be simply approximated to that of just one mode (the lowest in frequency), although attempts have been made to do so, [1]. The presence of multiple modes closely spaced in frequency in the dynamic response of trees to wind loading effects does however lead to some benefits. A form of natural "tuned mass" damping (as opposed to the inherent material and aerodynamic damping which is encompassed in the value of ζ_n for each mode) results from branch systems attached to the same tree structure that exhibit natural frequencies close to that of the tree itself. This not only has the effect of reducing the amplitude of the response, that would otherwise have resulted had these frequencies been more widely separated, but also makes the response more "broad band" (as opposed to "narrow" band) in character.

The influence of these effects can be ascertained by considering the complex Fourier transform of the response trace at the discrete location "m", given by $y_m(\omega)$, (where $\omega = 2\pi f$), which can be obtained from eqn. (2) as:

$$y_m(\omega) = \sum_{n=1}^{N} \phi_{mn} \left(\frac{\sum_{j=1}^{N} \phi_{jn} f_j(\omega)}{\left((\omega_n^2 - \omega^2) + 2\,i\,\omega\,\omega_n\,\zeta_n\right)} \right) = \sum_{n=1}^{N} \phi_{mn} \left(\left(\sum_{j=1}^{N} \phi_{jn} f_j(\omega) \chi_n(\omega) \right) \right) \quad (3)$$

in which $i = \sqrt{-1}$, and $f_j(\omega)$ represents the Fourier transform of the wind force trace at location "j" and $\chi_n(\omega)$ represents the "structure magnification" function for mode "n".

Now, introducing a wind speed to wind force model of the form

$$f_j(t) = \frac{1}{2} \rho\, C_d A_j\, V_j^{\,p}(t) \quad (4)$$

in which $C_d\, A_j$ is dependent upon the mean wind speed conditions (properties of foliage on tree branches in particular) and the exponent "p" may depart from the "classical" value of 2 to a lower value closer to unity [1]. Wind speed, V(t), may be characterised by a measurement at a single location, in which case correlation effects over the volume of the tree structure need be considered in modelling a tree's dynamic response to wind loading.

5. PROPERTIES OF CABLES IN TREE APPLICATIONS

The force displacement characteristics of single or groups of cables that form a cluster are not only dependent upon material properties but also upon geometric properties, (cable sag, in particular), which is governed by the level of pre-tension being used in each individual cable concerned. A typical load deflection curve for a cable is illustrated in Fig. 1, which is approx. linear only at high levels of force. When used in the context of tree systems, cables provide additional localised stiffness that can significantly influence the structural response characteristics of the tree limbs concerned as well as the tree's dynamic properties.

When the inter-limb response under wind excitation is sufficient to "momentarily" slacken an interconnecting cable, this event is often closely followed by a "snap tightening" condition in which the cable suddenly becomes taut and its tension force increases dramatically. The likely peak tension force in such a cable for any given wind storm may be able to be predicted from knowledge of the statistical distribution of the cable tension variation in such conditions. Data obtained from force measurements in cables during significant wind excitation events have been studied for their statistical properties. A Weibull variation for the upcrossing rates of these force records has been found suitable, viz:

$$\frac{N_x}{N_o} = \exp\left(-k\left(\frac{x}{\sigma}\right)^m\right) \quad (5)$$

where N_x and N_o represent the count of upcrossings in a record at level "x" of quantity x(t) (= F(t) - $\bar{F}$), viz the deviation of the force about the mean value, and at the mean force $\bar{F}$ itself, respectively, and σ is the standard deviation of x(t). If x were to be Normally distributed, (not possible here since clearly the force in a cable is always tensile, ie we can have positive only values for F(t)), then k=0.5 and m=2 which is indicative of a Rayleigh process for F(t). A value of m=1, on the other hand, would be indicative of a Poisson process for F(t), which situation is more realistic of cables in tree applications.

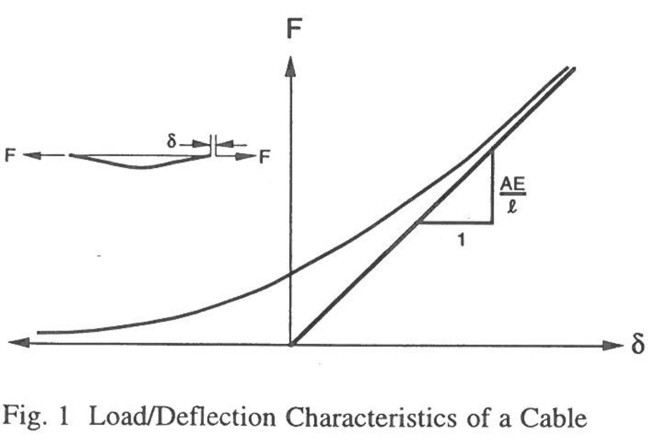

Fig. 1 Load/Deflection Characteristics of a Cable

6. SPECTRAL MODEL DESCRIPTION OF CABLE FORCE

Now, for any measure that is linearly related to displacements, y_m, in a tree structure (such as for example the force F in a taut cable which depends on the relative displacements of its two attachment points), the resultant spectral description can be simplified to:

$$S_F(f) = T^2(f)\, S_V(f) \qquad (6)$$

in which the transfer function, $T^2(f)$, characterises the relationship between the spectrum for wind speed at a reference point $S_V(f)$ and the spectrum for cable force $S_F(f)$ in a given tree. Consequently $T^2(f)$ essentially embodies the modelling descriptions of eqns. (3) and (4), the frequency dependence in its variation largely reflecting the frequency characteristics (dynamic properties) of the tree, ie the influence of the "weighted" sums of the $\chi_n(f)$ terms of eqn. (4), in particular.

Now, since $\int S_F(f)\, df = \sigma^2$, (a general property for a spectral variation) then knowledge of k , m and N_o in eqn. (5) under design wind conditions would allow evaluation of x_{max} (= $F_{max} - \bar{F}$) and the determination of the design cable force based upon the value of F_{max}. A logical framework for a rational design approach therefore exists based upon this spectral based modelling methodology.

7. CONCLUDING REMARKS

The use of steel cables to support trees and their limbs in urban areas is becoming a practice that is being questioned. Cable insertion changes the stress distribution in a tree structure and the properties of the tree's response to dynamic wind loading. The potential for damage to people and property and the increasing likelihood for litigation and liability claims from cable failure is of great concern yet there appears to be little guidance available from the literature that arborists can follow to come up with reliable cable design solutions.

This paper provides an overview of some of the key elements of a modelling strategy that would be necessary for establishing a rational design procedure for the use of cables in tree applications. Data collected from cable force measurements in strong wind conditions for a range of tree/cable configurations would be invaluable for establishing parameters necessary to this modelling strategy and for verifying the adequacy of any suggested "follow up" design procedure.

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