The Role of Branches in the Dynamic Response Characteristics of Trees

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Abstract

This paper describes the dynamic properties of trees and the significance of mass damping due to branches. The dynamic characteristics of trees with many branches can be modelled using a multi-degree-of-freedom system of tuned mass dampers which have a major influence on the dynamic properties and response characteristics of the tree.

Fundamental dynamic studies using "pluck tests" were used to investigate the tree-branch relationships on the dynamic properties of trees. The resultant vibration of branches (measured using accelerometers) in conjunction with the induced base-moment on the trunk of a tree (measured using the purpose designed base-moment device) were analysed to extract basic dynamic properties including natural frequency and damping ratios. Branches were progressively removed from the tree to convert the structure into a single degree of freedom system, and so demonstrate the high level of damping inherent in a standing tree.

Tree dynamic studies indicate that the multiple tuned mass damping of the branches provide a simple and effect damping mechanism which dissipates energy and minimises potentially dangerous harmonic sway modes from occurring. Trees have evolved over millions of years to become naturally damped structures and understanding the principle of their multiple tuned mass damping that dissipates energy may have implications for other vibrating structures such as buildings. Principles learned from trees may offer solutions in building design, particularly when energy dissipation is needed to damp out sway response caused by earthquakes.

Keywords: mass damping, wind, vibrations, frequency, branches, natural damped structures.

1. INTRODUCTION

The dynamic response of structures to dynamic excitation is of considerable interest in order to understand how structures survive and sometimes fail in catastrophic events from adverse vibrations such as from earthquakes, and extreme wind events. Construction materials such as steel and concrete are used by man to build quite stiff structures such as buildings, cranes, bridges. Structural materials in nature, however, are bones in animals and wood in trees (plants) and these materials are used to build load absorbing structures that are quite flexible and are observed to bend under dynamic loading. Is it possible to learn from the more flexible structures in nature to find principles that may be useful to apply in man-made structures? By studying how natural structures survive dynamic loading it may be possible to develop new ideas and introduce design concepts that may help absorb energy in dynamic situations for man-made structures, particularly those threatened by devastating collapse that may occur under extreme conditions such as in earthquakes.

This paper describes some recent research which investigates how trees use energy damping features to survive high energy dynamic excitation from extreme wind events. Trees have evolved over millions of years and are the largest living thing ever to exist on earth. The tallest trees are over 100 m in height and examples include the coast redwood of California, USA (*Sequoia sempervirens*) (The Gymnosperm Database 2008) and the mountain ash of Australia (*Eucalyptus regnans*), (Forestry Tasmania 2008). In discussing the storm-resisting features of the design of trees, Vogel (1996) suggests that a central theme is how nature uses flexible structures like leaves, branches, trunks, and roots. "Human technology mainly uses more rigid materials such as metals, ceramics, dry wood and so forth". The flexible structures and materials of trees not only twist and bend but do other things like absorb and either store or dissipate energy (Vogel 1996). Vogel suggests that we can learn from trees and the careful study of trees may reveal new concepts of behaviour of structures under dynamic loading.

Optimisation of shapes in structural design is desirable so that there are no weak points which will fail prematurely and also that there is no wasted material used to make other parts unnecessarily strong. Evolution in nature over millions of years has optimised the structural forms of bones in animals and trunks and branches in trees. The principle of optimisation applies to trees during growth so that all structural components are uniformly stressed and this concept is described by Mattheck (1998) who argues that there are strict biological laws in nature and that if we can understand nature's evolution in design, it may be possible to link this understanding to technology.

2. DYNAMIC RESPONSE OF STRUCTURES AND DAMPING

The dynamic response of a structure under earthquake or wind excitation can be modelled and approximated as either a single degree of freedom (SDOF) or a multi-degree of freedom (MDOF) system. Recent developments in buildings have investigated the more complex MDOF system models and the incorporation of tuned mass dampers (TMD). The concept of mass damping has been described in many engineering texts for mechanical systems and building structures (Connor 2002). Two translational tuned mass dampers weighing 270 tonne each were used on the 60 storey

John Hancock Tower constructed in Boston in 1975, to reduce the sway by 40 to 50%. The Citicorp Centre in Manhattan (1977) is a 279 m high building with a sway period of around 6.5 s. A tuned mass damper with a mass of 366 tonnes was located on the sixty-third floor and reduced the sway amplitude by about 50%. The mass damper of 366 tonnes saved an estimated 2800 tonnes of steel that would have been required to satisfy deflection constraints (Connor 2002). Fluid filled tuned mass dampers were used on the Centrepoint Tower in Sydney to reduce sway periods (Soong, 1997). Taipei 101 is one of the world's tallest buildings and uses a tuned mass damper consisting of a 730 tonne pendulum to reduce sway movement under wind loading by 40%. Early tuned mass dampers used complex mechanisms, relatively large masses and were quite expensive. Connor (2002) describes recent developments which minimise these limitations and use multi-level elastomeric rubber bearings, in a compact assembly that provides multi-directional damping with unsophisticated controls (Figure 1).

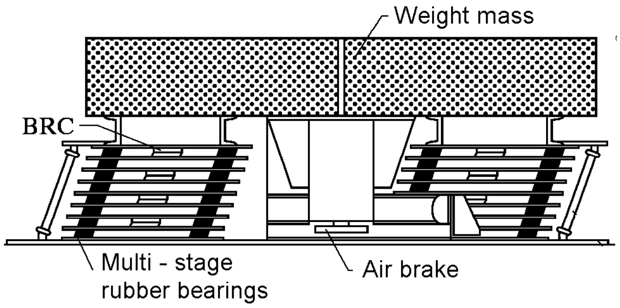


Figure 1. Compact tuned mass damper with spring and damper assemblage for buildings with unsophisticated controls (Connor 2002).

Multiple tuned mass dampers (MTMD) can also be used to reduce vibrations of floors in buildings (Saidi et al 2010).

Trees can also be viewed as structures and like all objects must obey the laws of physics (Niklas 1992). Open grown trees develop a branching structure as they mature and as their size increases, the forces of self weight and wind can also increase to levels that approach failure. Wind is the largest force on trees and under storm conditions can induce a dynamic response that can cause structural failure. Trees have optimised their structural properties to survive these extreme dynamic loading conditions by evolving a complex interaction of damping mechanisms, including mass damping where the branches sway out of phase with each other. The branches on a tree have a major influence on the dynamic properties and response characteristics of the tree that appears to have evolved an optimal configuration to minimise the sway response under wind excitation.

The tree and its many branches have been incorporated into a MDOF model (Figure 2) in which the trunk is represented as the primary oscillating mass, and the branches as a series of tuned mass dampers (James et al. 2006). The model is based on a primary mass, spring and damper element which represents the trunk with the branches being smaller representations of this primary element assemblage which is reiterated throughout the structure, in a manner similar to the real structure of a tree.

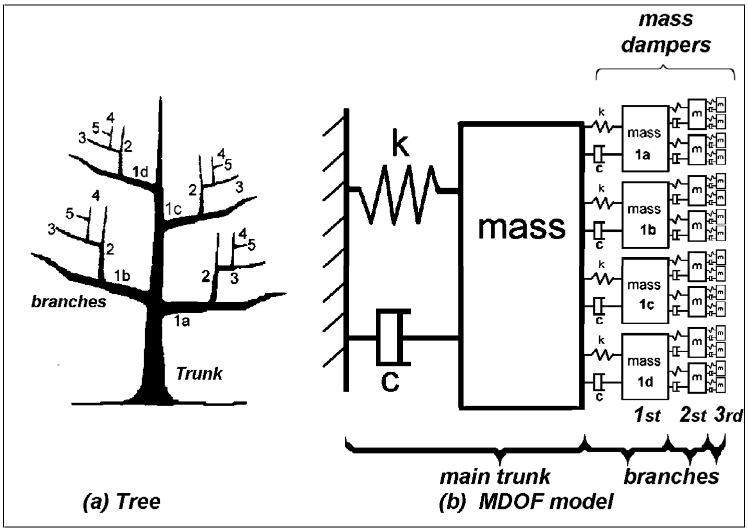


Figure 2. Dynamic structural model of a tree, showing the primary oscillating mass of the trunk and the tuned mass dampers of the attached branches (James et al. 2006).

3. METHOD AND RESULTS

The dynamic response of a tree was recorded by attaching strain meter instruments to the main trunk and using accelerometers on each of the main branches. The strain meter instruments measure the outer fiber elongation of the trunk as it bends and has been used to measure tree response under wind loading in a previous study (James and Kane 2008). Two strain instruments are 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. Recording at 20 Hz allows the instantaneous tree response to be accurately monitored so that dynamic data is captured.

A White ash (*Fraxinus americana*) with four main branches was selected from a site on a tree research plot of Davey Tree Expert Company, Shalersville, Ohio. The tree was 19.7 m high 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. Each of the four main branches was instrumented with an accelerometer (Gulf Coast Data Concepts, model GCDC X6-2) which was used as a tilt meter with an accuracy of 0.01 degree, and recorded at 20 Hz.

The branches were pulled with an attached rope then released to perform a "pluck test". The oscillations of the tree trunk and each branch were recorded from the instrumentation and the resulting time domain curve was used to fit the solution to Equation. 1 (Chopra 1995) which can be written as;

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

where: $\omega_d = \omega_n \sqrt{\left(1-\zeta^2\right)}$ or $\omega_d = \dfrac{\zeta}{\sqrt{\left(1-\zeta^2\right)}}$ and a is the initial displacement.

Noting that Equation (1) applies to a SDOF approximation to a tree which is a MDOF system.

An example of a branch response and curve fit is shown in Figure 3

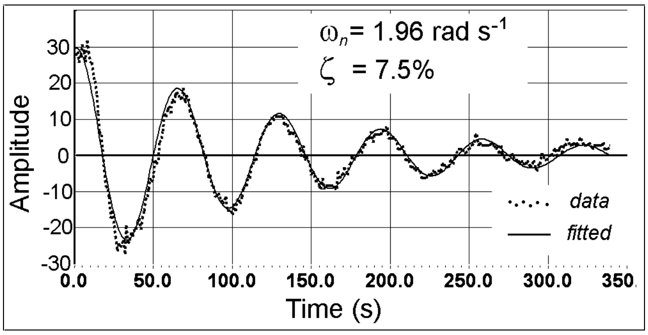


Figure 3. Example of data from pluck test of Branch 1, with curve fitted to determine frequency and damping ratio.

The pluck test was performed on the tree with all four branches attached, then repeated on the remaining branches and trunk as each branch was removed until only one bare branch was left for the final test.

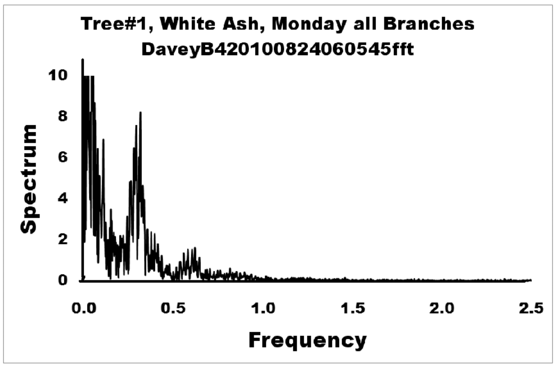
The results of natural frequency and damping ratio for all tests are shown in Table 1.

1. All Branches attached	ω nat frequ. (Rad/s)	f_o Frequency (Hz)	ζ damping ratio (%)
Branch1	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, 3 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, 2 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, 1 branch remains			
Branch1 with leaves	2.04	0.32	5.0
Bare branch	6.3	1.0	1.1
Trunk (1 bare branch)	6.3	1.0	1.1

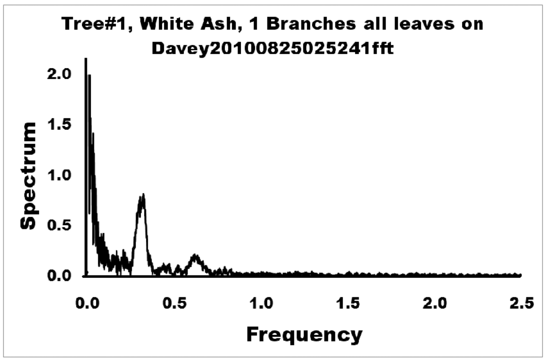
Table 1. Results from pluck test of tree with four branches, then the changes recorded as each branch was removed, until only one remained.

A spectral analysis was performed to examine the sway response of the tree trunk data. From this analysis, the natural frequency of the tree was found to be initially 0.33 Hz, and did not markedly change until three of the four branches were removed and only one remained. The damping ratio of each branch varied from 3.5 to 7.5% critical and varied depending on how the pluck test was performed, with higher values of damping ratio occurring when large sway amplitudes were induced. This we suggest is due to a larger relative velocity between the air and the branch for the large sway amplitudes, and consequently a larger aerodynamic drag component.

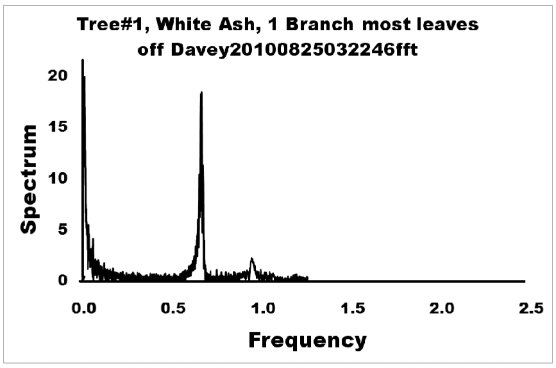
The damping ratio of the tree as a whole was approximately constant as the limbs were removed, and it was not until three of the four branches were removed, that a significant reduction in the damping ratio was recorded. The tree structure had to be modified so that it was reduced to a single pole before large sway oscillations were easily induced. Once the final leaves and small sub-branches were removed, it was possible to induce a second harmonic sway in the remaining branch (Figure 4d). The final dynamic response on the single pole structure had a higher fundamental frequency due to the reduction in mass once the small sub-branches and leaves were removed. The fundamental frequency changed from 0.33 Hz to 1 Hz, with a second harmonic frequency present at around 2.1 Hz.



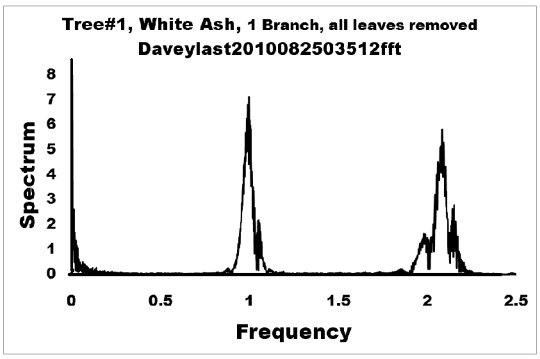
(a) All branches and leaves in place



(b) removed three branches, one branch left with leaves attached



(c.) one branch with half leaves removed.



(d) One branch no leaves, 2nd mode induced.

Figure 4. Spectral plots of data from pluck tests on a tree with (a) four branches, (b) three branches, (c) two branches and (d) one bare branch.

4. DISCUSSION AND CONCLUDING REMARKS

A tree with its many branches can be modeled as a MDOF system and by removing the branches, can be reduced to a SDOF system which resonates and exhibits low amounts of damping. The many branches of a tree act as tuned mass dampers and prevent the tree from developing large dynamic responses to excitation from winds or artificial pulling. The significance of this behavior is that the tree acts as a naturally damped structure that does not allow energy transfer from the wind excitation to develop dangerous harmonic sways within its structure. The total damping is complex and has components of aerodynamic damping, mass damping and internal or viscoelastic damping due to internal damping and energy dissipation in the root structure.

The principle of damping observed in trees provides a simple and comprehensive damping mechanism which may have application in other (man-made) structures. Because tuned mass dampers are used in buildings to provide energy dissipation and prevent dangerous sway occurring, it is suggested that the multiple tuned mass damper model from trees may have application in some buildings. A concept of distributing TMD's throughout a building, rather than having one large TMD could offer economical and practical solutions for dissipating energy in buildings prone to earthquake excitation. One concept could include retro-fitting a medium sized building of 4 to 6 floors, with liquid TMD's in the form of half filled water tanks at the end of the top few floors. If the first mode frequency of the dampers was tuned to the first mode frequency of the building, this concept could provide a simple and effective method for dissipating energy during earthquake excitation.

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