The effects of leaves and steel support cables on northern red oak with co-dominant trunks

Mark Reiland

ISA certified arborist #SO6233A

Research Objective

- Determine the effects, if any, that steel support cables and leaves have on the dynamic properties of large, co-dominant deciduous trees.
    - Natural sway frequency
    - Damping ratio

Natural Sway Frequency

- The natural sway frequency is the number of cycles the structure (tree) will complete in a given time, usually 1 second.

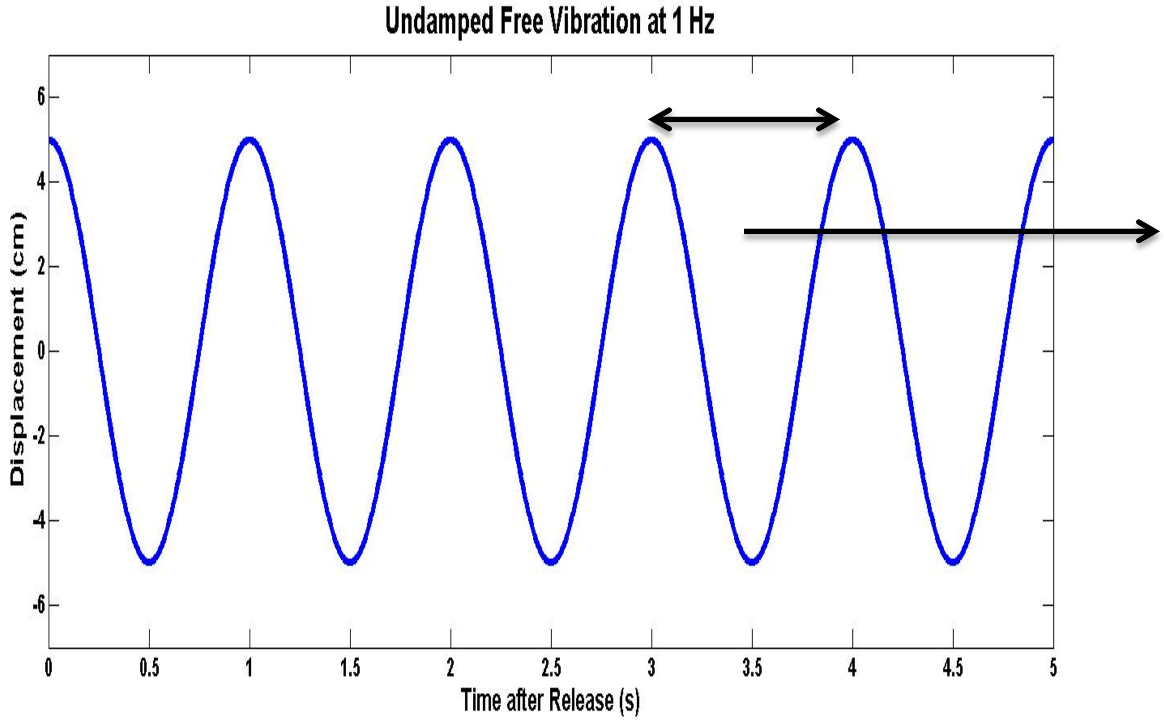
$$\omega_n = \sqrt{\frac{k}{m}}$$

Where:

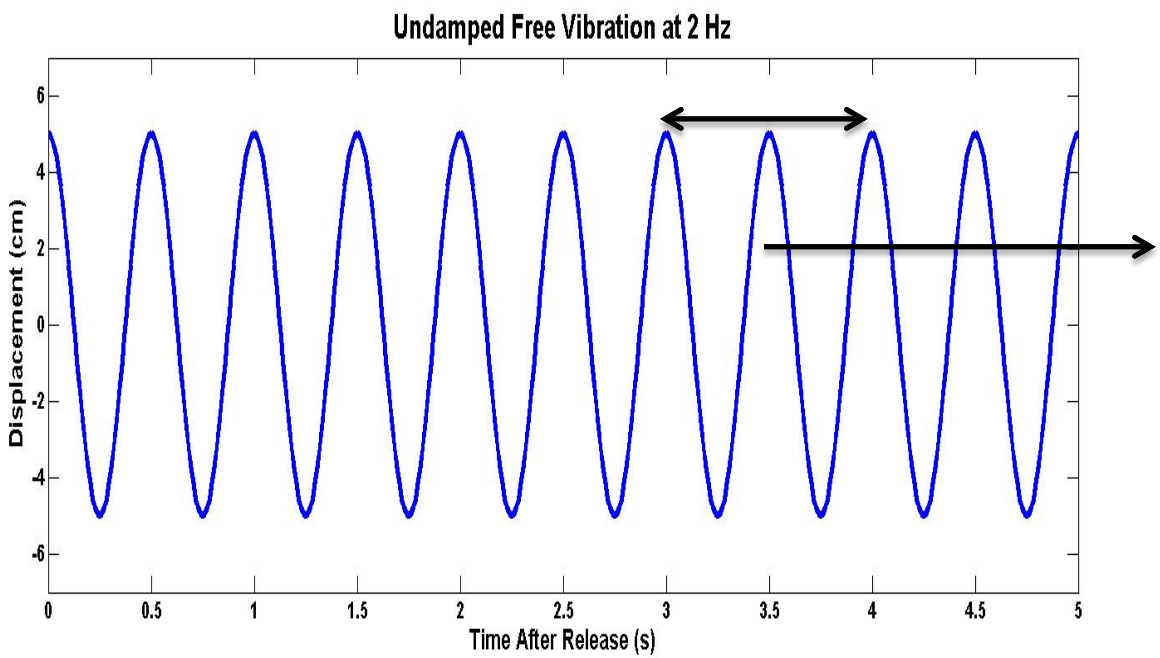
'ω_n' is circular frequency (rad/s)

'k' is the equivalent stiffness

'm' is the mass



Structure completes 1 cycle
in 1 second
Frequency = 1 Hz



Structure completes 2 cycles
in 1 second
Frequency = 2 Hz

Damping Ratio (ζ)

- Damping ratio expresses the efficiency of a structure to dissipate motion energy
  - Overdamped

    $\zeta > 1$
  - Critically Damped

    $\zeta = 1$
  - Underdamped

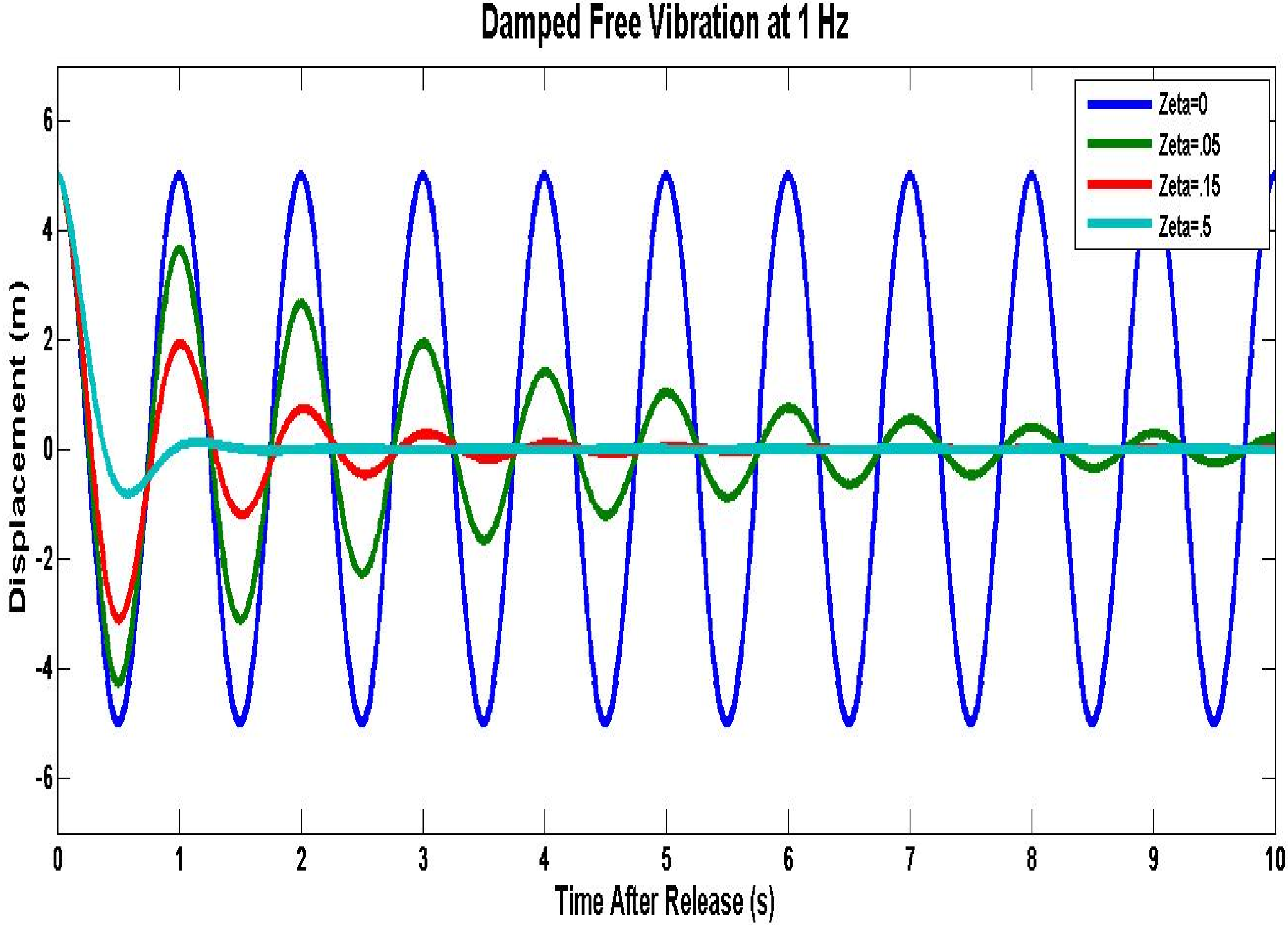
    $\zeta < .25$

$$\zeta = \frac{c}{c_{cr}}$$

Where:

C = damping coefficient

c_{cr} = critical damping coefficient ($2\sqrt{km}$)



As ζ increases, successive amplitudes of displacement decrease more rapidly i.e. motion energy is dissipated more quickly.

Methods

- 10 similar sized co-dominant northern red oaks trees selected
  - 5 were cabled, 5 were not
- Free vibration testing performed during winter 2012 (leaf off) and summer 2012 (leaf on)
  - Acceleration time history recorded at trunk height just below co-dominant union (+/- 30.5 cm)
  - Natural sway frequency and damping ratio determined from acceleration time history

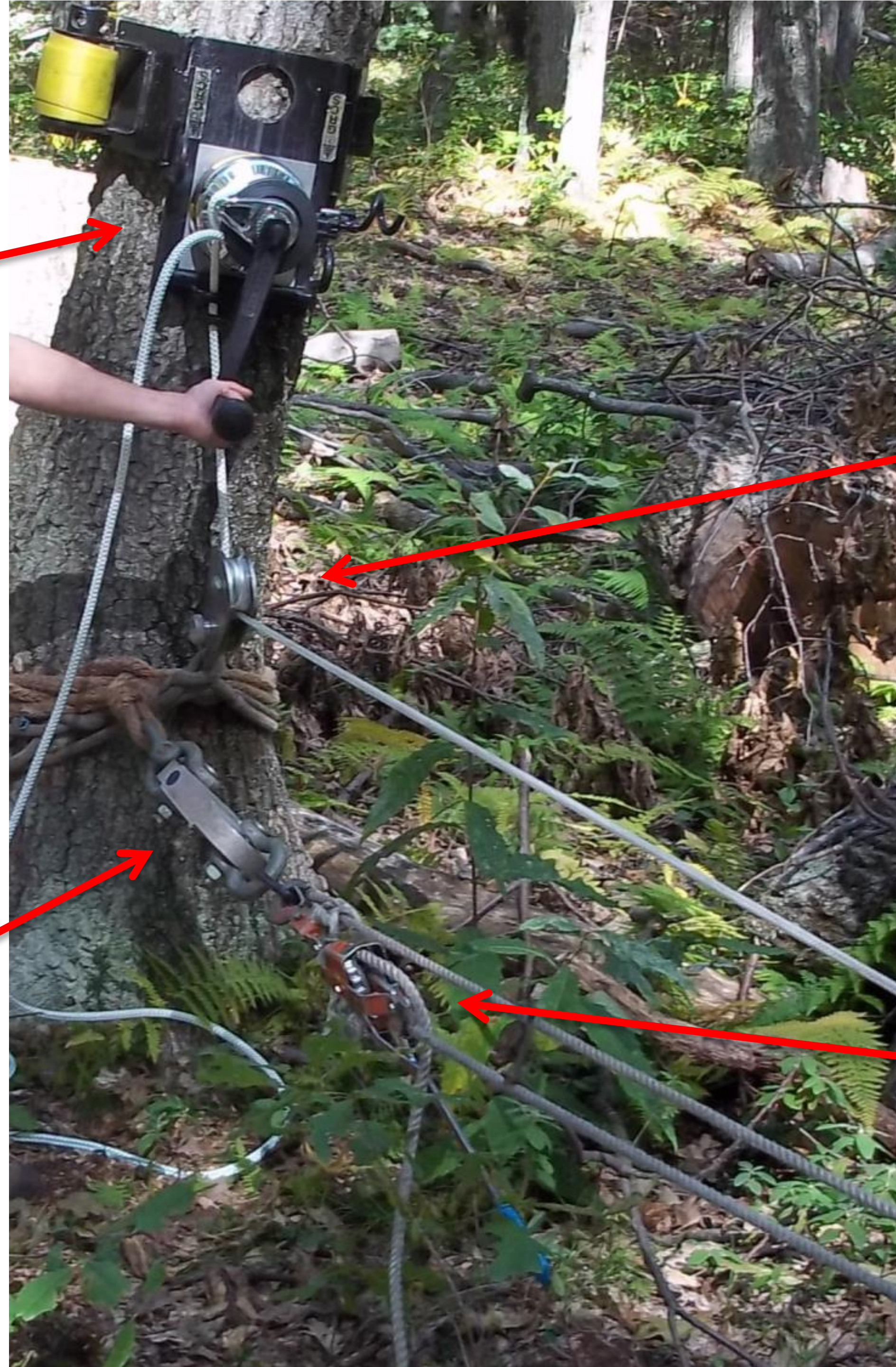
Morphologic characteristics of sample trees

	N	DBH (cm)	Height (m)	Height to Union (m)	Cable Span (m)	Cable Tension Leaf On (N)
Cable	5	42.9 (4.46)	21.9 (3.07)	11.0 (1.19)	2.9 (1.27)	49.3 (20.01)
No Cable	5	42.1 (4.02)	20.9 (2.59)	13.9 (2.81)	1.1 (0.09)	~~~~~


Accelerometer
Antenna to data logger
Plumb bob for measuring initial displacement

GRCS used to tension the pull line

Re-direct for pull line into GRCS

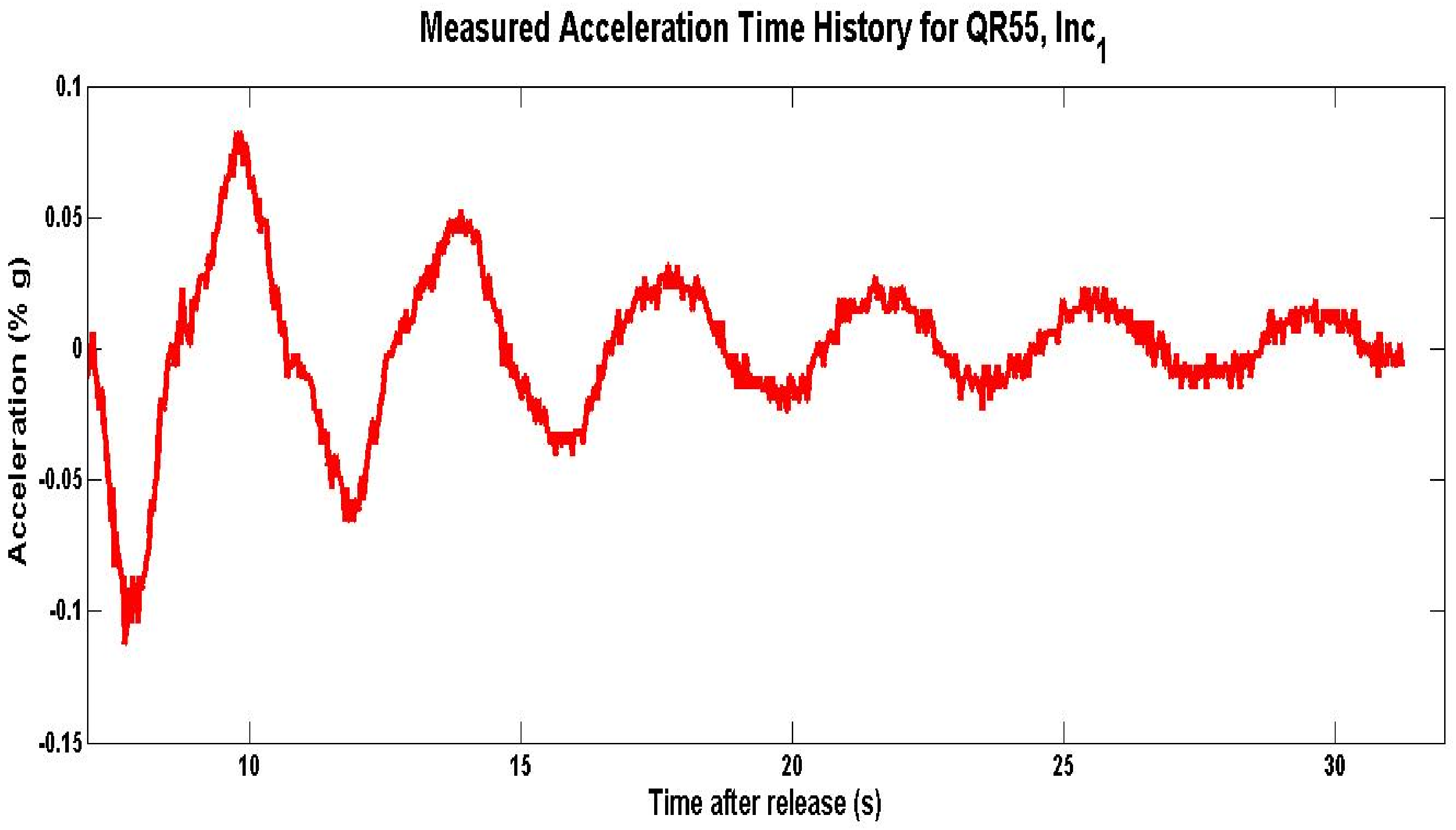


Load cell for measuring initial tension in pull line

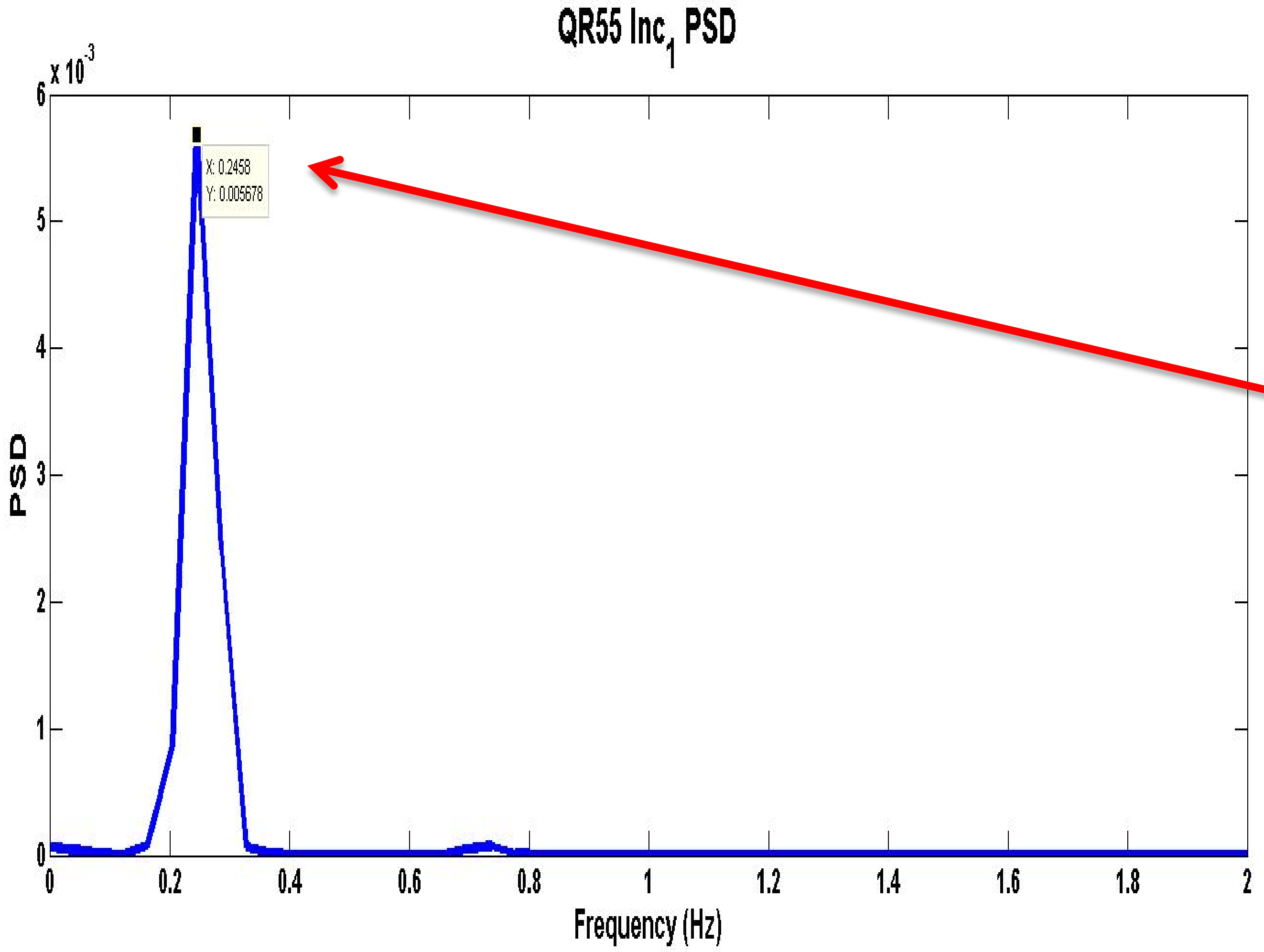
Continuous rope puller with 2:1 mechanical advantage anchored to load cell

Pull line to GRCS
Continuous rope puller to load cell
Location where pull line was cut with hand saw to release sample tree
Re-direct for pull line from sample tree to tensioning assembly

Acceleration Time History



Power Spectral Density Plot



PSD Plot has well defined peak at .2458 (.25) Hz

ζ Calculation

- ζ was calculated using the half power bandwidth method and the PSD plot.
  - Repeated six times for each tree per leaf condition.
    - 3 times in incident direction and 3 times in orthogonal direction in both leaf off and leaf on conditions

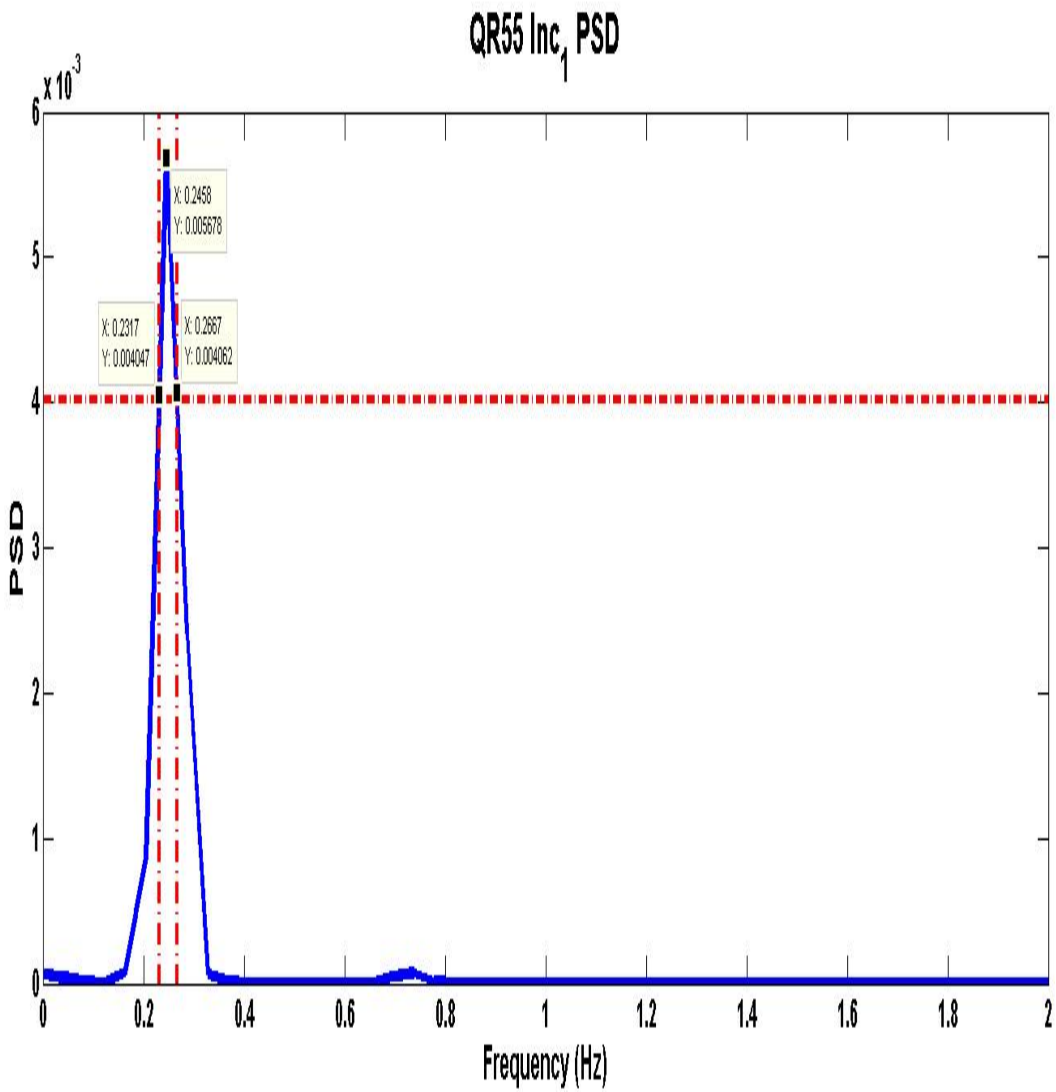
$$\zeta = \frac{f_b - f_a}{2f_n}$$

Where:

$f_{a,b}$ are frequency values occurring at $\frac{1}{\sqrt{2}}$ the amplitude of the peak value in the PSD plot

f_n is the frequency value corresponding to the peak in the PSD plot

Half Power Bandwidth Calculation



f_a = .232 Hz

f_b = .267 Hz

f_n = .246 Hz

$$\zeta = \frac{f_b - f_a}{2 f_n}$$

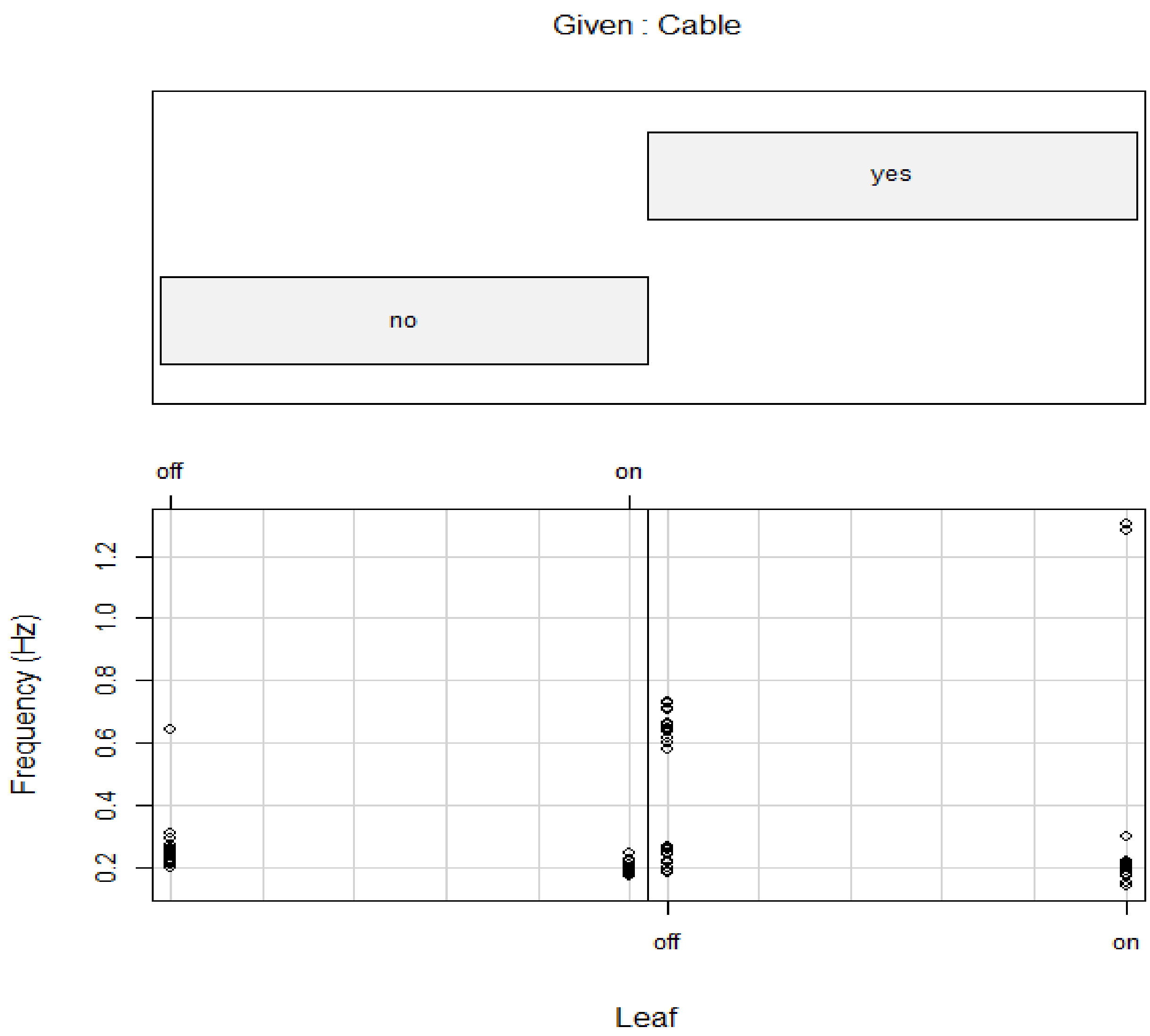
$$= \frac{.267 - .232}{2 * .246}$$

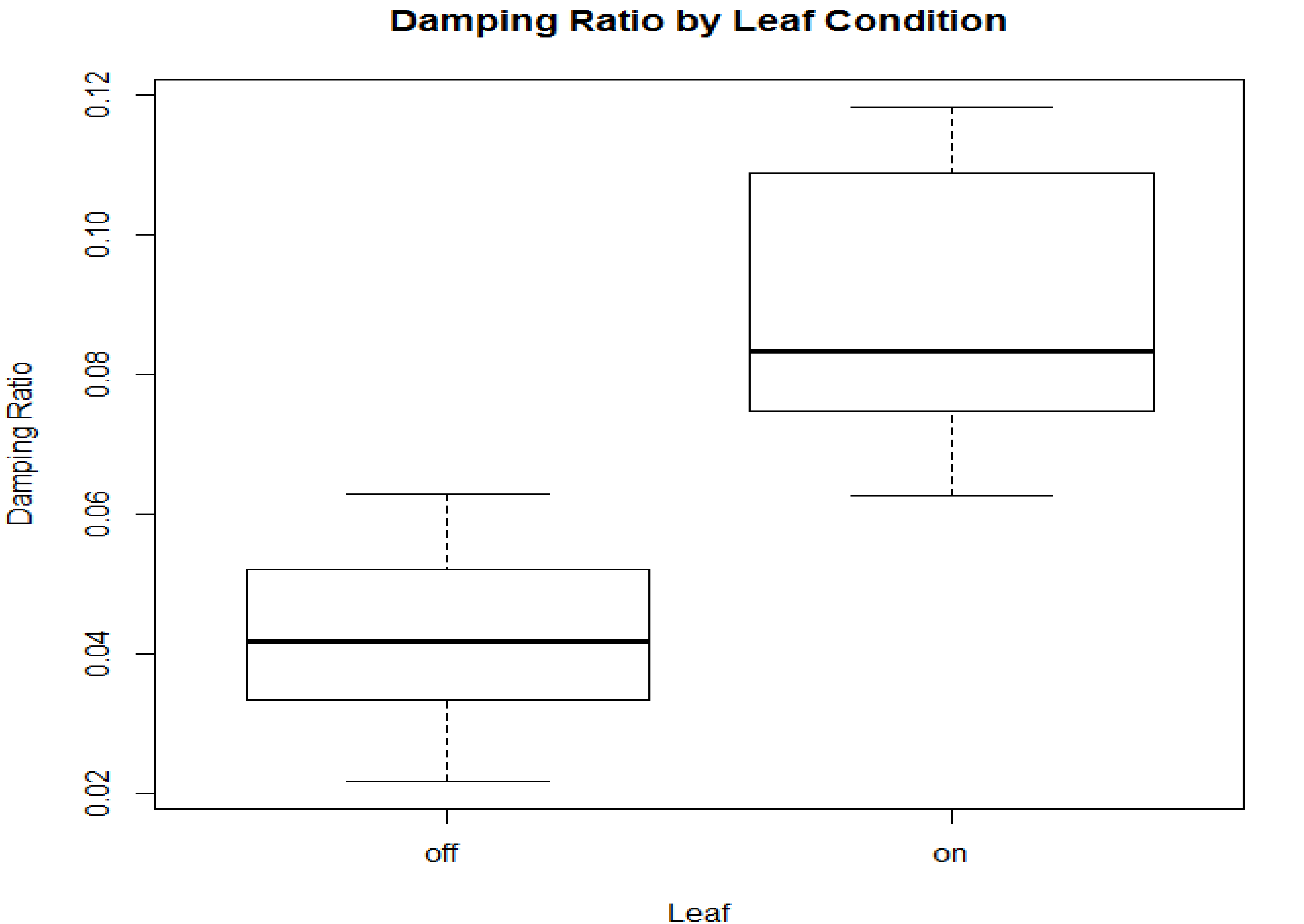
= .07 = 7%

Results

- Both cabling and leaf condition had a significant effect on the frequency of sample trees.
  - Cabled trees had higher frequencies than non-cabled trees.
  - Trees in the leaf on condition had lower frequencies than trees in the leaf off condition.
- Only leaf condition had a significant effect on damping ratio.
  - Trees in the leaf on condition had significantly larger damping ratios than trees in the leaf off condition.

Frequency by Cable and Leaf Condition




Damping Ratio by Leaf Condition
Damping Ratio
0.02
0.04
0.06
0.08
0.10
0.12
off
on
Leaf

Cable Effect on Frequency

$$\omega_n = \sqrt{\frac{k}{m}}$$

Cable ⇨ k ↑

ω_n ↑

Cabling increases stiffness of 2 primary branches between co-dominant union and cabling location without changing the mass. The increased stiffness corresponds to an increase in frequency.

Leaf Condition Effect on Frequency

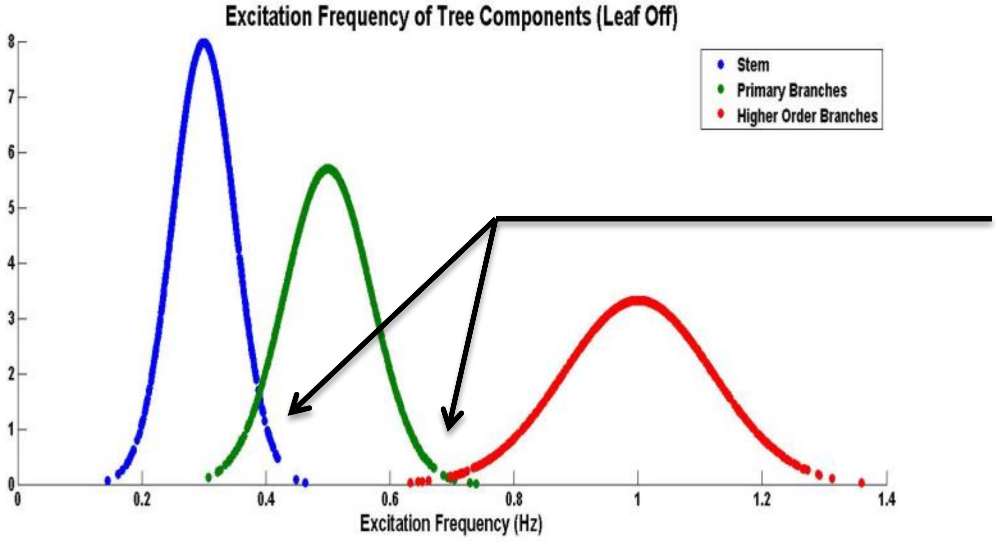
$$\omega_n = \sqrt{\frac{k}{m}}$$

Leaf On ➡ m ↑

ω_n ↓

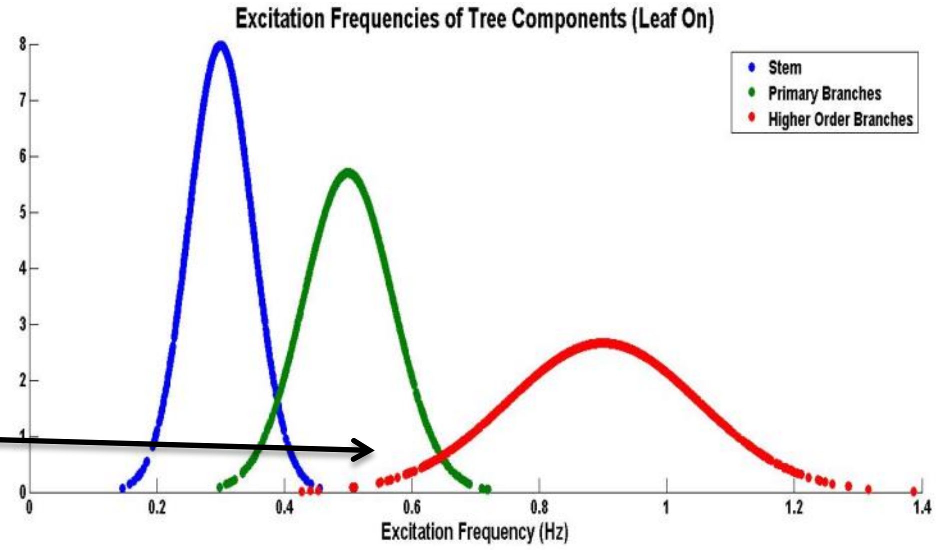
The presence of leaves in the canopy increases the total mass of the system without changing the stiffness of the system. The increased mass corresponds to a decrease in frequency.

Leaf Condition Effect on Damping Ratio

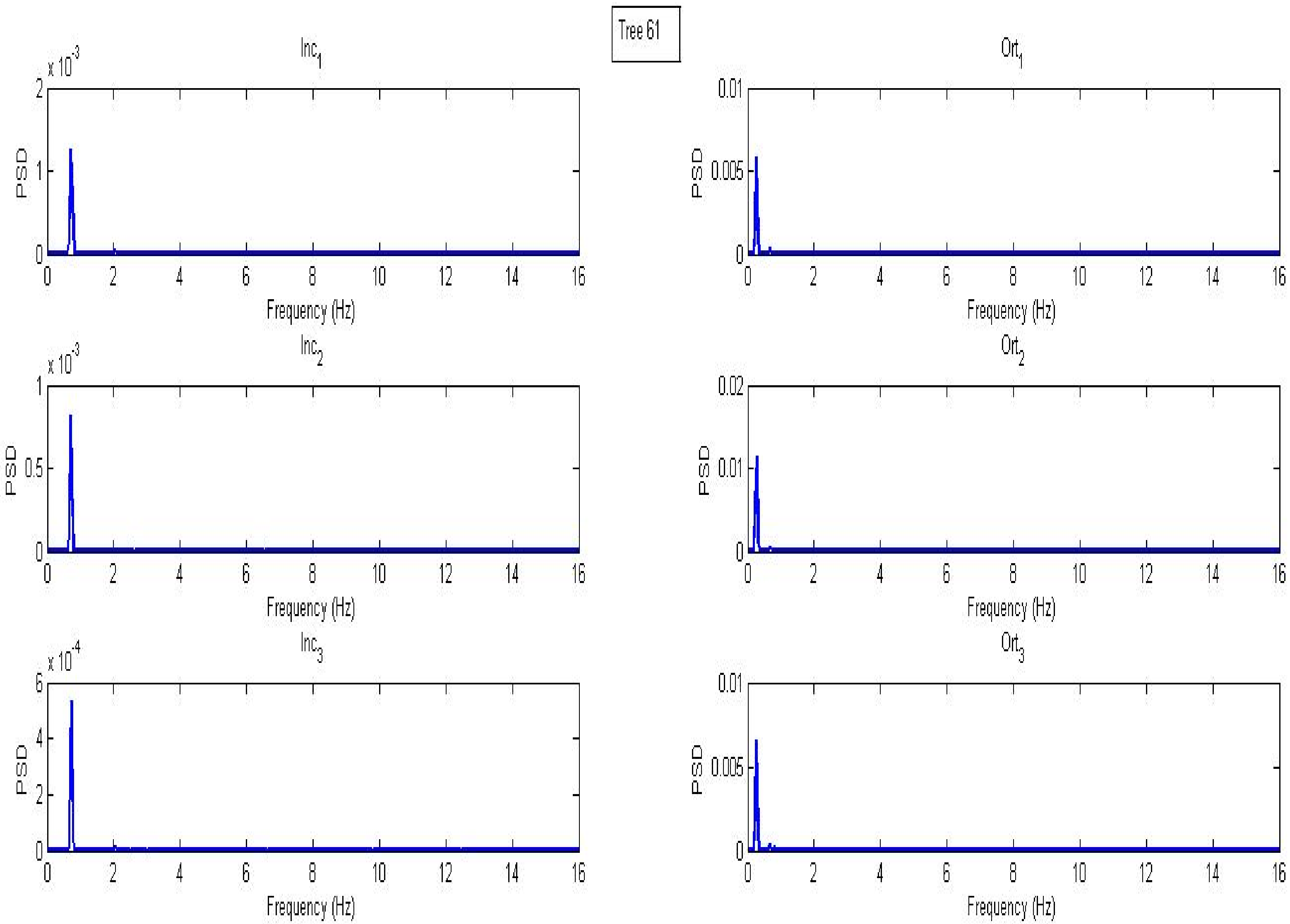


Energy is transferred from stem to primary and higher order branches because of overlap in the frequency bands of the different components of the tree.

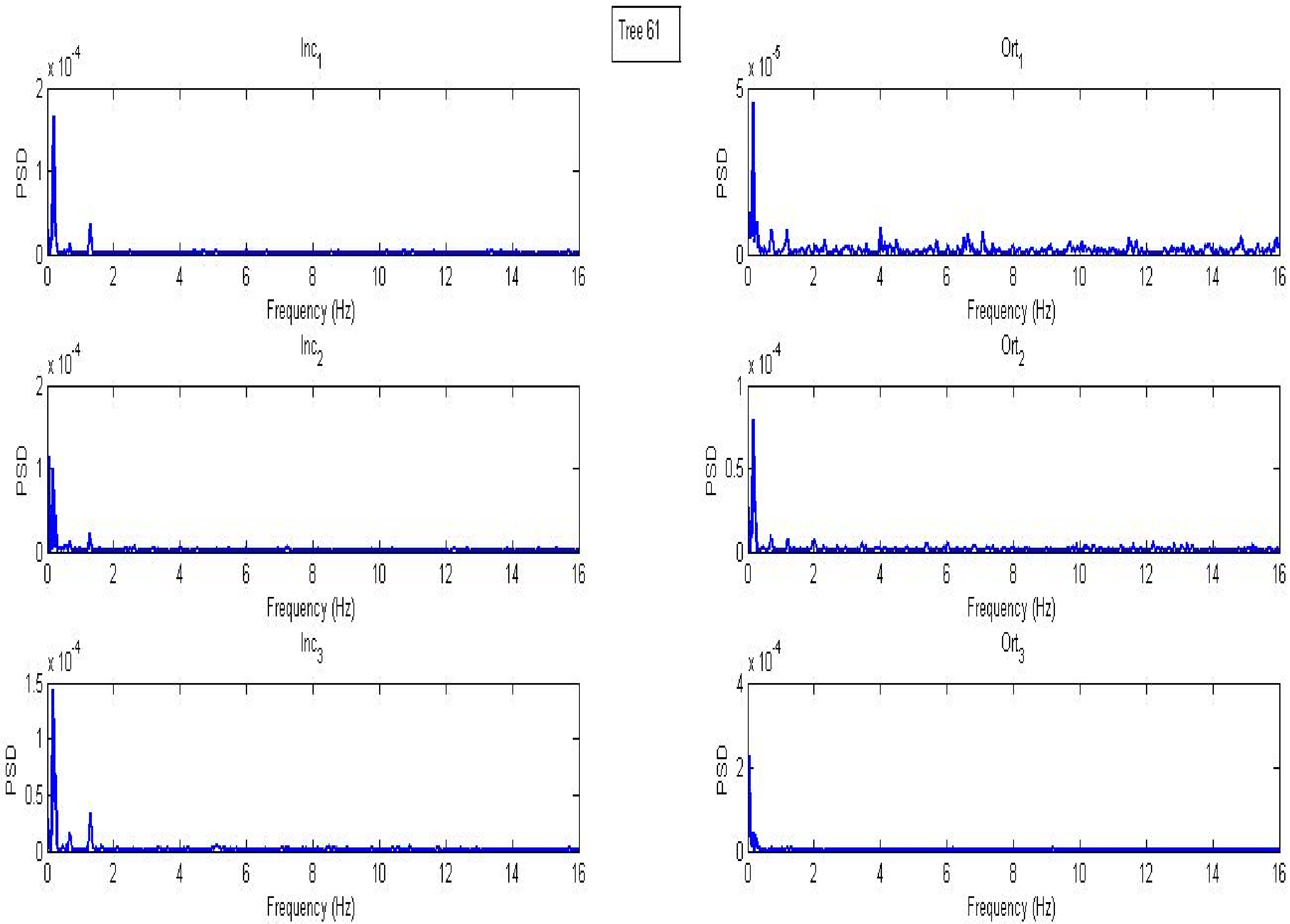
The additional mass of leaves causes a decrease in the frequency of second and higher order limbs causing an increase in frequency band overlap with the stem and primary branches.



PSD Plots, Leaf Off

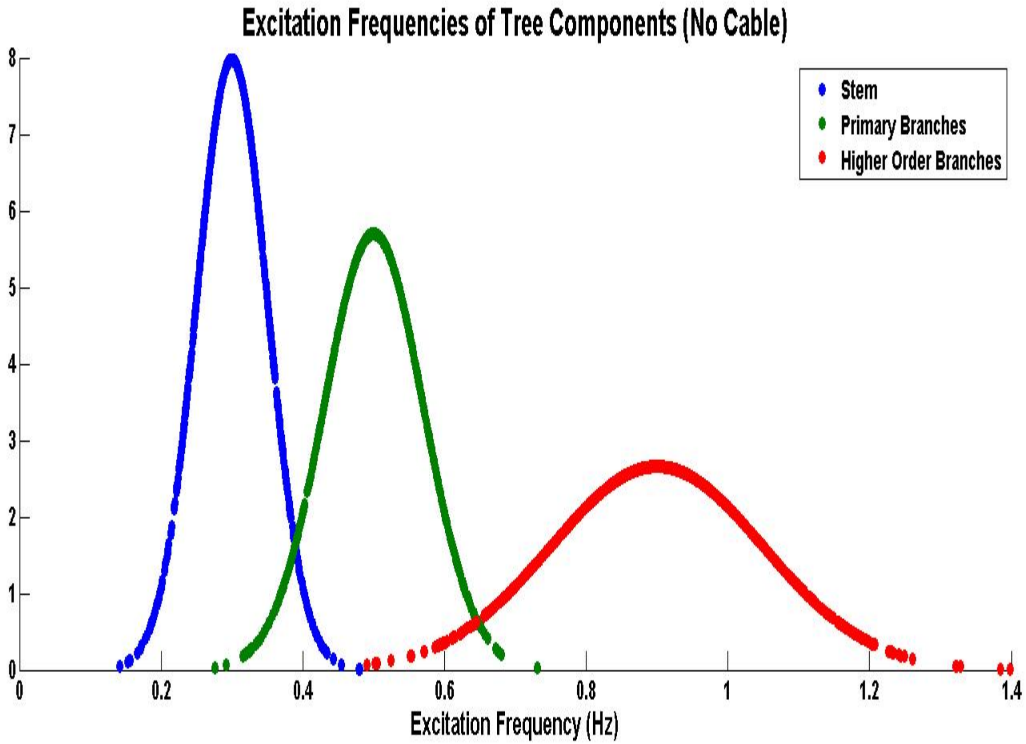


PSD Plots, Leaf On



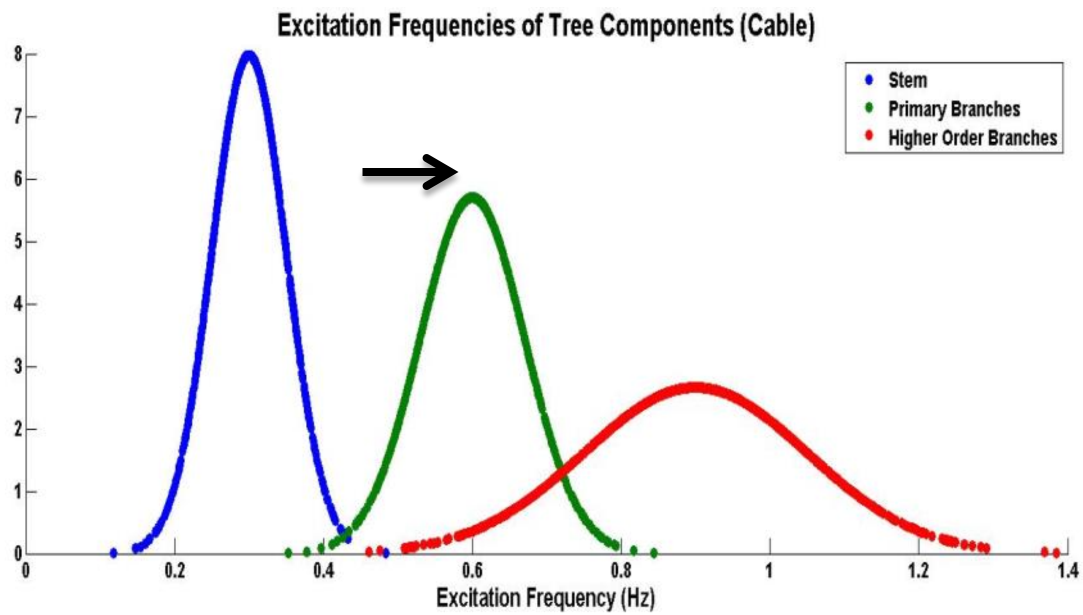
Practical Considerations for Arborists

- Maintaining frequency band overlap is critical to preserving the trees ability to dissipate stress and prevent failure.
- Excessive pruning of higher order branches during cabling operations could interrupt the transfer of energy from different components of the tree.
- Pruning treatments were not included in this study.



1.) Theoretical tree frequency band overlap before cable installation

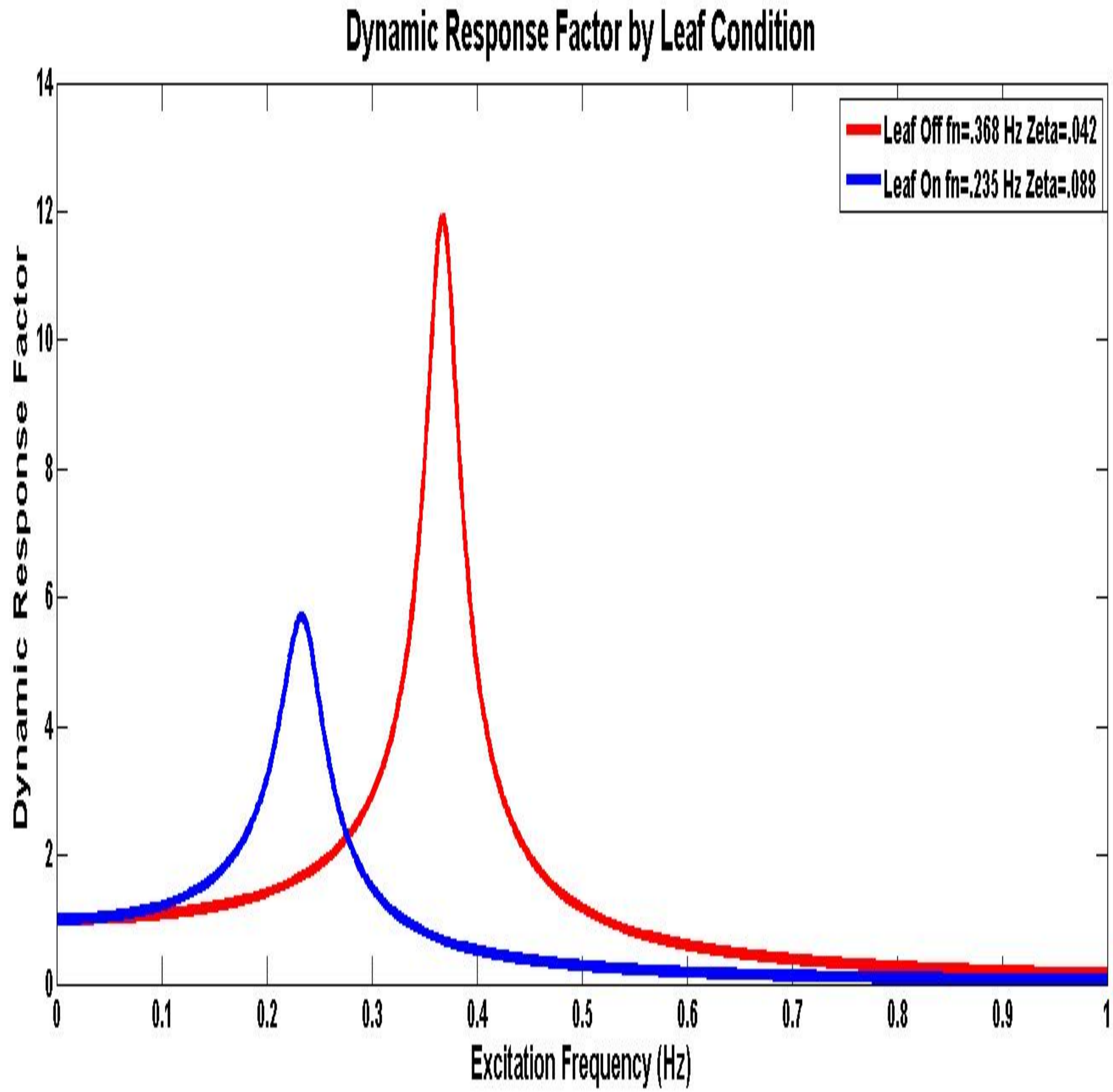
2.) Post cabling frequency band overlap. The frequency band of the primary branches (green) has shifted to higher frequencies.



Practical Considerations for Arborists

- Previous work has shown the effect of pruning on frequency and damping ratio is more pronounced in the leaf off condition.
    - This is also true for the effect of cabling on natural sway frequency.
- It is important to understand the type of stresses that trees are subjected to in their environment (dynamic vs. static)

Dynamic Stressors



$$R_d = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\left(\frac{\omega}{\omega_n}\right)\right)^2}}$$

Location and amplitude of peak values are dependent on both the natural frequency and damping ratio of the tree.

Dynamic vs Static Stressors

- Dynamic stressors such as wind loading cause dynamic responses in the tree whose amplitude is dependent on natural frequency and damping ratio.
  - Ideally, the maximum damping ratio should be preserved in all arboricultural operations.
- Static stressors such as snow and ice loading affect the tree over long periods of time and more closely mimic static analyses dependent on material (wood) properties.

Conclusions

- As trees are underdamped structures, the maximum amount of damping should be preserved in all arboricultural operations.
- Further research is needed to determine the effect of pruning treatments in conjunction with cable installation.

Acknowledgments

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Questions