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Application Note

AL100: Optimizing Accelerometer Placement in Trees - Preliminary

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INTRODUCTION:

The “best” (or optimum) sensor placement is a significant question when attempting to use an accelerometer to monitor the swaying motion of a tree. If you place the sensor too close to the ground, there is very little motion. If you place it too high, it is difficult to place and then to service. This report may not answer this question in all cases, but it attempts to provide a better understanding of the factors that make the placement at least acceptable if not “optimum”.

What is Optimum?

Of course, “optimum” is somewhat in the eye of the beholder, and not everyone will have the same criteria for what constitutes “optimum”. Here are a number of criteria that may be useful.

- **Sufficient signal** - This is probably the number-one consideration for everyone who puts an accelerometer in a tree. There is no point in trying if there is not enough signal in the recorded data. Otherwise, it is a wasted effort. This is difficult to determine before-hand and is the subject of most of this report.

- **Accessible** - Unless the experiment lasts a shorter time than the battery life, you will need to access the sensor to replace batteries. If the experiment lasts long enough, you may need to replace the memory card. Either can be very difficult hanging from a climbing harness. Don’t forget that there are small parts and dropping one from high in a tree could be catastrophic, especially if the small part is the memory card!

- **Simple Attachment** - The AL100 can be attached with screws but many will object to inserting screws into a tree. Plus, it may simply be difficult to insert screws or other hardware on many kinds of trees. If the tree diameter is very large, it may be difficult to get cord or a rubber “bungee” around the tree.

- **Protected -** The sensor needs to be located where it will not be subject to “abuse” by animals, machinery, or humans.

Placement for Signal

Choosing the placement to guarantee sufficient signal is not a trivial task. It is relatively clear-cut for a tall tree with relatively few lower branches (example: rain forest Mahogany). It is less clear for common conifers (example: Douglas Fir). It is even less clear for multi-stemmed trees (example: Birch or Poplar). And, for a tree that branches profusely above a relatively short trunk (example: Oak, Walnut, or Maple), the choice is quite unclear.

Lets start with the simplest case. A tall, slender, tree with its foliage concentrated at the top is very close to the classical "cantilevered beam" that was first described, mathematically, by Euler and Bernoulli around 1750. There are many possible combinations of anchor and load but the one that fits our tree case is very close to a point load near the end (top) of the beam (tree) rigidly anchored at the other end. The formulation we will use is presented in "Engineer's Edge" [1] This equation gives the deflection, y, at various points along the beam (distance = x, measured from the anchored end of the beam) for a load W applied perpendicular to the beam at the far end of the beam (distance = L measured from the anchored end of the beam). The parameter E represents modulus of elasticity (Young's Modulus) of the beam and I represents the moment of inertia of the beam:

$$y(x) = W\, x^2\, (3L - x) / 6EI$$

At the point where the load is applied, x = L and we have

$$y(L) = W\, L^3 / 3EI$$

We, however, know nothing about W, E, or I. But, we can estimate the amount of deflection at the top of the tree. Lets call that Yo, that is Yo = y(L), solve that for W / EI and substitute that back into the equation for y(x):

$$W / EI = 3Yo / L^3$$

$$y(x) = [x^2\, (3L - x) / 6]\, [\, 3Yo / L^3\,]$$

$$y(x) = Yo\, x^2\, (3L - x) / 2\, L^3 \quad \text{[EQN 1]}$$

So, lets try an example. Suppose that the tree is 50m tall and sways +/-0.5m about its resting position at the top of the tree. How much movement will there be 1m above the ground? In this example, L = 50m, x = 1m, and Yo = 0.5m. Then,

$$y(1m) = 0.5 * 1^2\, (150 - 1) / 2 * 50^3$$

$$y(1m) = 74.5 / 2 * 50^3$$

$$y(1m) = 74.5 / 250{,}000$$

$$y(1m) = 0.29mm$$

At the likely sway frequency of such a tree, this would be barely detectable, at best, by the AL100.

The important thing, here, is that the amplitude of the motion is critical, but it is NOT sufficient. The issue of “sufficiency” is addressed in the next section.

What about other tree shapes?

A tree with a strongly tapering trunk, such as most conifers, will bend more where the trunk is smaller diameter. Thus, you would expect LESS horizontal displacement than predicted by the previous equation. On the other hand, many large conifers are NOT tightly anchored to the ground; you can feel the ground (near the base of such a tree), itself, shift when it is windy. Thus, prediction of EQN 1 might under-estimate or it might over-estimate, depending on the size of the tree and the soil conditions.

For multi-stemmed trees, the question is whether you are measuring the motion of the tree, as a whole, or that of one of the individual stems. After observing several such trees (Birches), it appears that if an accelerometer is placed on a secondary stem near the main trunk, the primary motion will be that of the tree as a whole. If you place the accelerometer further out on the secondary stem, the motion of the individual stem will dominate.

For trees with short, central, trunks and which are strongly branched, above (Oak, Walnut, Maple, for example), there may be little or no “whole-tree” motion. Most of the swaying seems to take place in the individual branches. For such trees, little guidance can be given at this point.

Sufficiency Conditions for Good Signal

As suggested in the previous section, high enough amplitude is necessary, but not sufficient. The reason for this lies in the basic relationships of motion.

Lets start, here, by assuming that the motion is sinusoidal. It generally won’t be precisely like a sine, but this assumption will demonstrate a very important principle. If the motion has a frequency of F (“sways” per second, or Hertz - Hz) and has an amplitude A (that is, it sways a distance +A away from resting, then back to -A away from resting), the displacement can be written as:

$$y(t) = A \sin (2\pi F\, t)$$

Now, we should know that velocity is the first derivative is displacement, or

$$v(t) = dy(t)/dt$$

$$v(t) = A\,(2\pi F)\cos(2\pi F\,t)$$

And, if our General Physics is not too rusty, we should know that acceleration is the first derivative of velocity, or

$$a(t) = -A\,(2\pi F)^2 \sin(2\pi F\,t) \quad \text{[EQN 2]}$$

Importantly, an accelerometer measures a(t), NOT v(t) or y(t)! The coefficient "A" is the displacement estimated by EQN 1. From this equation, we should be able to see that the acceleration depends on BOTH the displacement, A, and the sway frequency, F.

The PEAK acceleration occurs every time $\sin(2\pi F\,t) = 1$ (or -1) and is $+/-A\,(2\pi F)^2$.

As an example, lets suppose that a tree sways at 0.5Hz (2 second period) and with a displacement of +/- 1cm = +/- 0.01m. The peak acceleration for this example is then

$$a_{max} = 0.01m * (2\pi * 0.5)^2$$

$$a_{max} = 0.01m * (\pi)^2$$

$$a_{max} = 0.0986m/s/s$$

which we can round to $a_{max} = 0.1m/s/s$.

This is an important number, but the AL100 is calibrated in terms of "g", the standard gravitational acceleration, which is 9.80665 m/s/s.

Thus, our example acceleration can be expressed in g rather than metric acceleration as (about) 0.01g.

The AL100 has a sensitivity of (about) 20µg per bit at a sample rate of 10Hz. Then, the example case would result in a reading of about +/- 500 counts.

But, what about the earlier example of a 50m tree measured at 1m above the ground? Its displacement was about 0.3mm. If this tree also has a sway frequency of 0.5Hz, then the acceleration measurement would be 500 counts * (0.3mm/1cm) = 15 counts. That might be hard to get reliable data from. If the sway frequency is lower (because of the relative height of the tree), then it might be difficult to separate out the signal from noise.

What would be the solution? Raise the placement of the sensor on the tree. Doubling the height to 2m would mean about a 4X increase (shown by EQN 1) in signal!

About the Sway Frequency

The frequency of vibration of a cantilever beam with a mass, M, at the free end, is given by [2] :

$$F = (1/2\pi) \sqrt{[\ 3EI / (\ 0.2235\ \rho\ L + M\ )\ L^3\ ]} \quad [EQN\ 3]$$

E, I, and L are as previously defined. M is the mass at the end of the cantilever and ρ is the mass per unit length. The term (0.2235 ρ L + M) represents the total effective mass of the system.

Note that the frequency given in EQN 3 is for the lowest bending mode (one node at the anchored end of the cantilever). There are other, higher frequency modes.

This equation does not help us, very much, to estimate the sway frequency of trees. However, it DOES show us something about how that frequency changes with a number of physical changes of a tree.

For example, we might expect ρ and M to vary diurnally as water uptake dominates or transpiration dominates. M and ρ PROBABLY reach a maximum in the morning when the transition is made from water uptake to transpiration and PROBABLY reach a minimum in the evening when the transition is made from transpiration back to water uptake.

For trees with a concentrated canopy at the top of the tree, M should increase, perhaps markedly, during rainfall.

On the other hand, the modulus of elasticity, E, may vary with the amount of water held in the trunk.

L is unlikely to change diurnally, but can certainly change over a growing season. M & ρ may also increase over a growing season. M & ρ will likely change markedly in deciduous trees as leaves develop in the Spring and fall in the Fall.

Accessibility

For many installations, 2m is a practical maximum height. That is about the maximum working height without ladders or other equipment. However, if the sensor is mounted this high, it is quite difficult to get the lid off, to replace batteries, or to swap the memory card unless there is something to stand on.

For many conifers, the lower branches can be so dense that it is difficult to access the trunk more than a meter or so above ground. This seems less of an issue with many broad-leaf trees but should still be taken into account.

Attachment

The AL100 enclosure has two "mounting tabs", top and bottom, with screw holes. These holes are sized to accommodate M4 or number 8 screws. Use "pan head" or "round head" rather than "flat head" screws to avoid damage to the enclosure.

However, many users may not want to attach with screws.

The author has used rubber "bungee cords" very effectively. One at the top and one at the bottom will go over the mounting tabs. If trunk size allows, a single bungee (or several connected, end to end) wrapped twice around the tree is even more effective. In this configuration, the criss-cross of the bungee on the back side of the tree insures that the bungee will not easily come off the mounting tabs.

Other materials such as nylon cord, rope, "zip-ties", and such, can also be effective.

No matter what the mounting method, you want to insure that the position of the sensor does not shift. This can cause changes in sensitivity over time. Plus, it may simply fall off!

Protection

For most situations, logging equipment probably is the only mechanical threat. If logging is possible, take care about the tree on which sensor is mounted.

Animals do represent a threat in many places. Bears that climb trees are certainly capable of damaging an accelerometer. It is unknown how squirrels and other small animals will treat one. In some places, there may be wild cats that regularly climb trees. Again, if you know about the presence of such animals, some care is warranted.

Humans can always be a threat. If the general public has access to the study area, the best strategies are probably to install it in an obscure location. Camouflage may also be helpful. If necessary, spray paint it! If you use bungee cords to mount the unit, choose colors that do not stand out against the tree trunk.

Mounting Orientation

There have been questions about the "best" mounting orientation. If the mounting surface is nearly vertical, then it is usually easiest to mount the AL100 with the mounting tabs at the top and bottom.

In this orientation, you can ignore the X axis. It only shows gravitational acceleration since there is very little movement in the vertical direction. Not recording the X axis can mean improving the battery life by as much as 30%! The axes to be recorded are controlled through the USB terminal interface.

Conclusions

Mounting height is not the only factor in determining the strength of the acceleration signal when mounted on a tree. Tall trees with low sway frequencies can also be difficult. The optimum mounting height MAY depend on the shape (trunk structure) of the tree.

Accessibility can be an important consideration. How the accelerometer is attached is also important. The author likes bungee cords but other temporary attachments also work.

The accelerometer does need to be mounted firmly and in a location that avoids animals, people, and machinery.

References:

[1] https://www.engineersedge.com/beam_bending/beam_bending9.htm accessed August 20, 2015

[2] www.vibrationdata.com/tutorials2/beam.pdf accessed August 20, 2015