

Measuring weight fluctuations in trees based on natural frequency

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Master thesis

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Abstract

Satellite-based soil moisture measurements indicate a diurnal variation in backscatter in west Africa. This diurnal variation is assumed to be caused by variation of moisture content in vegetation (Friesen, 2008). The obtained satellite soil moisture data can be improved, if ground measurements support this hypothesis. Especially at locations with a dense land cover, where the satellite can't penetrate into the soil improvements can be made. Currently there are no easy applicable methods to measure vegetation water content continuously, which can assist in confirming the relation between vegetation water and the satellite measurements.

In this research a new non-destructive, cheap, easy applicable and continuous method to measure water content in trees is developed. This new method makes use of the variation in natural frequency caused by the diurnal variation of water content in trees. The natural frequency of a tree depends on its stiffness and its mass. Diurnal variations in the mass of a tree are mainly caused by changes in water content. To determine the natural frequency two methods are tested. The first method makes use of the wind as a driving force and the measurements are analysed in the frequency domain. The second method uses a single pulse as driving force and the measurements are analysed in the time domain. To confirm the validity of the proposed analyses both methods are first tested on simplified system (a stick fixed in a vice). Different weights are attached to the top of the stick to relate weight and frequency changes. The vibration of the simplified system and of trees are measured with an accelerometer. To determine the natural frequency both systems are modelled as a damped first order spring-mass system.

Results indicate that, for the simplified system, changes in natural frequency are detectable and can be related to mass changes of the system. When the methods are applied on a tree the accuracy of the measurements is not high enough to identify changes in weight, caused by variation in water content. It is possible to measure the natural frequency of a tree but the changes in natural frequency due to changes in water content are very small (less than 0.1 Hz for small trees). For the simplified system the weight changes compared to the own weight of the system are much larger. Presumably, this is the main reasons for the difference in performance between the simplified system and measurements on a tree. Additionally, the simplified system is better represented by a first order spring-mass system. Previous studies have indicated that the anisotropic mechanical properties of a tree, prevents it from behaving like a first order spring-mass system.

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Preface

I started this research thinking I was going to investigate the cause of diurnal variation in soil moisture content observed in satellite data from west Africa. A new method needed to be developed to measure the water content in trees. Rolf Hut and Nick van de Giesen came up with the idea to measure natural frequency changes of trees and relate them to water content. The new method seemed promising so shortly after starting I went to Ghana to collect measurements of trees. It turned out we were a bit too optimistic. Developing a new method like this just takes more time and effort. A lot of testing and data analyses have to be done before it is actually possible to implement a new method. When developing a new method a lot of things will come up unexpectedly the data you collect will never be perfect. This even holds for field measurements performed with a well-established method.

In the end this research is not about the investigation of diurnal variation of soil moisture but about the development of a new method to measure variations in water content. Development of this method incorporates aspects of several different disciplines. The development was initiated because of the interest in soil moisture. For this method tree movements were measured which requires understanding of the tree mechanics. To understand the mechanics and frequency responses, understanding of physics is necessary. Additionally proper analysis of the data requires signal processing. The necessary knowledge of this disciplines certainly moved beyond the normal water management curriculum and were a nice challenge to become familiar with.

As research always has its ups and downs there were times during this research when I got really frustrated with trees. During those times the song of Luuk and Gijs 'bomen zijn relaxed' made me remember that all the trees had the best intension with me. They weren't the cause of the difficulties faced during this research, or maybe they were but at least they didn't intent to cause these difficulties.

Finally I want to thank my committee Nick van de Giesen, Susan Steele-Dunne, Bob Ursem and especially Rolf Hut which gave me a lot of feedback and new ideas to tackle encountered problems. My friends and family were always there when I needed support for or a break from my research. Of course I also want to thank Frank Ohene Annor for his help and hospitality during my stay in Ghana.

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1 | Introduction

Only 0.15% of the liquid freshwater on earth is soil moisture (Dingman, 1994), still this is an influential water storage in the hydrological cycle. Soil moisture is a very important parameter for a wide range of fields: hydrology, agriculture, ecology, climatology, meteorology (Douville and Chauvin, 2000). Soil moisture is a central parameter which has influence on a lot of other important fluxes in hydrological modelling such as temperate, precipitation evaporation and transpiration (Dunne et al., 1975).

A difference in microwave backscatter data of morning and evening (10am,10pm) satellite overpasses of the European Remote Sensing (ERS) satellite is observed (Friesen, 2008). The detected diurnal patterns are not in accordance with the natural moisture patterns found in the Volta Basin (Friesen, 2008). The largest differences coincide with the onset of water stress, suggesting that the diurnal variation in backscatter might yield useful information on water availability in the root zone (Steele-Dunne et al., 2012). The detected diurnal variations in satellite data showed systematically behaviour, both in space and time, different from variations in regional soil moisture. An analysis of possible causes for the diurnal variations leads to the hypothesis that water in vegetation is the main cause of the observed patterns in satellite data (Friesen, 2008). To confirm this hypothesis new field observations are needed. providing more accurate satellite soil moisture estimates, and extracting vegetation water states. The diurnal backscatter differences could then be used as an indicator for the onset of drought.

In this research a new non-destructive method to measure relative water content in a tree is developed. The method will be a cheap, continuous and easy to perform method. The dynamic characteristics of a tree are analysed to find the natural frequency. The dynamic characteristics of a tree will be influence by a lot of factors: shape, stiffness, temperature, moisture content etc. (Gerhards, 1982). The movement of the tree is measured with an accelerometer attached to the tree trunk just below the start of the crown. The data will be observed in the time and frequency domain.

The central question in this research is,

Can daily frequency fluctuations of trees be measured with an accelerometer?

The tree is modelled as a first order spring-mass system to determine the natural frequency of the tree. This means the following simplifications are made:

- The crown is a point weight on top of the trunk
- The trunk is a weightless beam
- The tree is symmetric in all directions
- The damping is only caused by the stiffness of the trunk

Because this research is only interested in natural frequency and not in damping ratio and amplitude, it is possible to directly analyse the accelerations. This is convenient because 'zero drift' will occur with the conversion from acceleration to displacement. The natural frequency, mass and stiffness are directly correlated. The assumption is made that the fluctuations in mass of a tree during a day are mainly caused by changes in water content of the tree. Another important assumption is that changes in weight have a significant influence on changes in natural frequency of a tree. This must be the most important influence, because this method is based on the relation between weight and natural frequency.

This method has already been applied in the form of a rain gauge (Stewart et al., 2012). For the rain gauge a bucket was attached to a steel post. The steel post was modelled as a first order spring-mass system, the movement of the steel post was measured with an accelerometer to determine the natural frequency. An increase in water collected in the bucket showed a clear relation to the frequency of the system (Stewart et al., 2012).

This research will first describe the relation between weight changes and frequencies for a controlled system. A wooden stick with different weights attached to its top is used as a representation of a damped first order spring-mass system. Subsequently the method will be applied to trees.

Research outline

To start the anatomy and growth development of trees is explained. The focus of this research is on the relation between anatomy and the mechanics. The forces a tree gets to endure during its life time have a big influence on the growth of a tree and thus on its dynamic behaviour. The methods and models which are commonly used for the analysis of the dynamic behaviour of trees are explained and will be used during this research.

In chapter 3 | Methodology, the approach to develop the new measurement method is explained. Two different experiments are performed. A control experiment on a stick and the experiment on a tree. Both experiments are performed with two different energy inputs, a single pulse input (referred to as sway-experiment) and the wind (referred to as wind-experiment) are used as driving force. The movements measured during the wind-experiment are analysed in the frequency domain and the movements measured during the sway-experiment are analysed in the time domain. Both systems (the stick and the tree) are modelled as a damped first order spring-mass system.

In the results and discussions presented in chapter 4 | Results and discussion, the movement direction of the tree is analysed first because it has been shown that a tree have different mechanical characteristics in every direction. To analyse the relation between weight en natural frequency the results found during the experiments on a stick are presented, followed by the results found during the tree experiment. In addition an analysis of the influence of the time interval chosen for the wind-experiments is presented.

Chapter 5 | Conclusions, is divided in 5 subjects. The accuracy of the method, the movement direction, the experiment setup, differences between the stick and a tree and the model used will be discussed.

To round up some suggestions for further research have been made in chapter 6 | Recommendations.

2 | Background on Trees

There are over 25000 different tree species known in the world with a wide range of mechanical characteristics (Thibaut et al., 2001). In this research the dynamical characteristics of trees are of interest. Tree dynamics have been studied to get inside in several different topics such as, wind throw (Ulanova, 2000), tree height (Friend, 1993) and climate (Wade and Hewson, 1979). The anatomy of a tree is explained first, followed by the mechanical properties of a tree and the factors which influence these properties. Thirdly the previous research done on the natural frequency is presented. The previous studies have mainly focused on frequency difference on a large scale, for example the frequency difference between different trees or the frequency differences of a tree with and without branches (Milne, 1991). Two methods are commonly used to analyse the tree dynamics these will be explained. The data gathered with these methods is analysed with a couple of different models describing a tree. The model chosen depends on the goal of the research.

2.1 Anatomy

For a tree it is important to have a large leaf surface to use solar light and CO₂ for photosynthesis from the surrounding air. To do so the structural parts of a tree are just strong enough to support the developing crown. A tree has two separate growing mechanisms referred to as primary growth and secondary growth. Primary growth determines the architecture topology of the branches. This is done with two different growing processes, elongation of the already existing branches and the creation of new branches. Secondary growth occurs after the creation of new branches and the elongation. A cylindrical layer is developed under the bark around the same time as elongation takes place. This layer is called the cambium. The cambium can produce new wood in successive cylindrical layers. When a branch is observed in the cross-sectional direction the cylindrical layers are visible as growth rings. The growth rings can give an indication of time related parameters. The rings with a low cambium age have a significantly different mechanical behaviour (lower stiffness, higher extensibility). For a tree all the mechanical properties are strongly correlated to the specific gravity. This is due to the cellular building of wood. Factors which influence the mechanical properties of wood are the temperature, the moisture content and the loading conditions. The growth mechanism of a tree are presented in Figure 1.

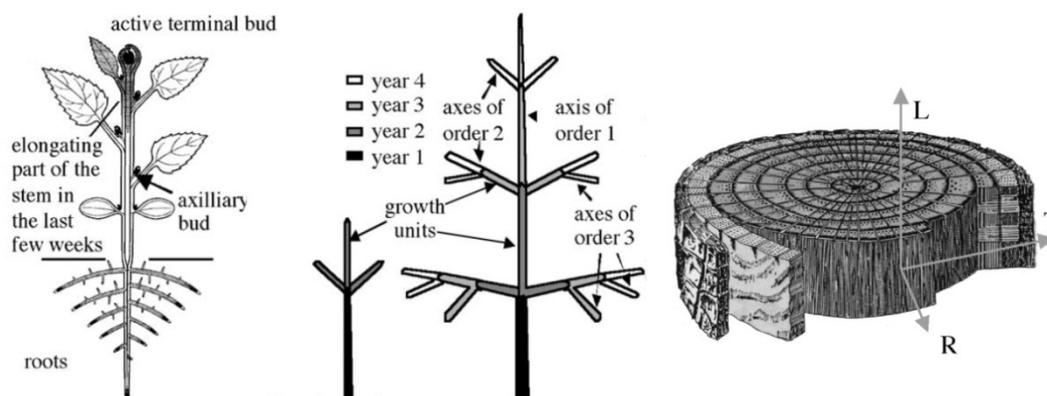


Figure 1: Growth mechanism of a tree the two left pictures display primary growth and secondary growth in the right picture, taken from Thibaut et al. (2001).

The woody parts of a tree do not only serve to deal with all the forces a tree has to endure. They also serve to link all the different parts in a tree and support the circulation of food, fluids and information. The time of the year influences the type of cells which are mainly produced. Each annual growth ring will consist of a denser layer produced during summer and a porous layer produced during spring. For a lot of trees the 'summer wood' is 2 to 4 times stronger than the 'spring wood' (Thibaut et al., 2001). An Increment borer can be used to analyse difference in growth rings of the tree trunk (Grissino-Mayer, 2003).

Natural variation in relative moisture content of a tree is estimated to be around 20% (Hunt and Rock, 1989). This is very species depended. Research indicated that the mechanical properties of trees changes with fluctuations in moisture content and temperature. Changes of 6 to 20% in moisture content are most interesting for changes in mechanical properties. The mechanical properties changes most when the moisture content decrease beneath the fibre saturation point, which is around 30% moisture content (Gerhards, 1982).

2.2 Mechanical properties

The mechanical state of a tree is the result of the combination of load variation, maturation processes and wood layer accumulation. To get an idea of the stress distribution in a tree the following factors have to be taken into account, the evolution of mass and geometry of the structure, the loading history, the maturation stress and the mechanical equilibrium of the tree. The history of loading and growth is determining the total stress distribution. This is also referred to as growth stress (Thibaut et al., 2001). The tree size, shape and structure influence the mechanical properties of a tree under dynamic loading. The building of the trunk, crown lay-out and root system all contribute to the anisotropic mechanical properties of a tree.

When a tree grows it increases in weight and will develops a greater self-loading, because it gets higher the tree is also exposed to higher wind velocity. This will result in higher bending moments at the base of the tree. Research shows that the own weight of a tree and hydraulic factors limit the maximum tree height (Koch et al., 2004). A tree must be able to withstand all the forces it endurance during its life time. The wind is the biggest force most trees have to withstand, especially the wind gusts (Jacobs, 1936). Factors which affect the photosynthesis such as water and sunlight mainly determine the tree growth. But biomechanical constraints set limits on the tree size and shape and thus the growth of a tree, even if the parameters which influence the photosynthesis are not exceeded (Spatz and Bruechert, 2000). The concept that a tree adapted his growth to mechanical forces is already quiet old. This concept stated that the tree develops a trunk shape that is optimized to handle horizontal and vertical forces (Metzger, 1893). The cambial activity is controlled by the movement of the tree. The exact relation between cambial activity and tree movement is still not fully understood, some proposals have been made such as the 'constant stress theory' but has already been rejected by other authors (Gaffrey and Sloboda, 2004).

The growth of branches is also depending on physical parameters. The tree tries to achieve a minimization of sway motion and stresses. Branches have shown to be a critical factor in damping of the tree. The tree constantly responds to forces it gets to endure either by growing or by shedding branches. A dynamic balance can be achieved by the slow grow response or by the fast reaction of shedding branches. In medium winds small twigs will be shed to maintain the bigger structure. In strong winds larger branches can fall of or even the main trunk can break. A tree tries to minimize the energy transferred from the wind to the tree. A smaller crown or in general smaller trees will catch less wind and the aerodynamic drag will be lower. Dynamic mass damping will minimize the occurrence of resonance frequencies and will reduces the amount of energy transferred to the trunk and root system of the tree. This will lead to a bigger stability of the tree (James et al., 2006)

All these adaptations of trees to external factors not only changes the shape of the tree but also the physical and mechanical properties of the wood itself. This properties have a great variation in the vertical and horizontal direction due to changes in density, annual ring width and reaction wood. Reaction wood will form at the points where the tree 'feels' stress. Reaction wood includes both tension wood and compression wood. Tension wood is normally produced at the upper side and compression wood is normally produced at the underside. Reaction wood is formed to bend the leaning stem upwards toward vertical by contraction in the case of traction wood and by expansion in the case of compression wood (Wilson and Archer, 1977).

The root system of a tree is a very important for the stability of the tree it is shown that the root system is an important factor in the above ground movement of the tree. The shape of the root system is influenced by the site specific conditions such as water table depth, soil properties and the main wind direction (Coutts, 1983). The layout of the root systems is greatly influenced by the wind, the structural root mass is bigger on the leeward side than on the windward side (Nicoll and Ray, 1996). Not only the root system adapts to the wind force, the shape of the individual roots also adapts to experienced forces Figure 2. The left picture shows a root with a T-shape and the right picture shows a root with an I-shape, which are both well-known shapes in constructions.

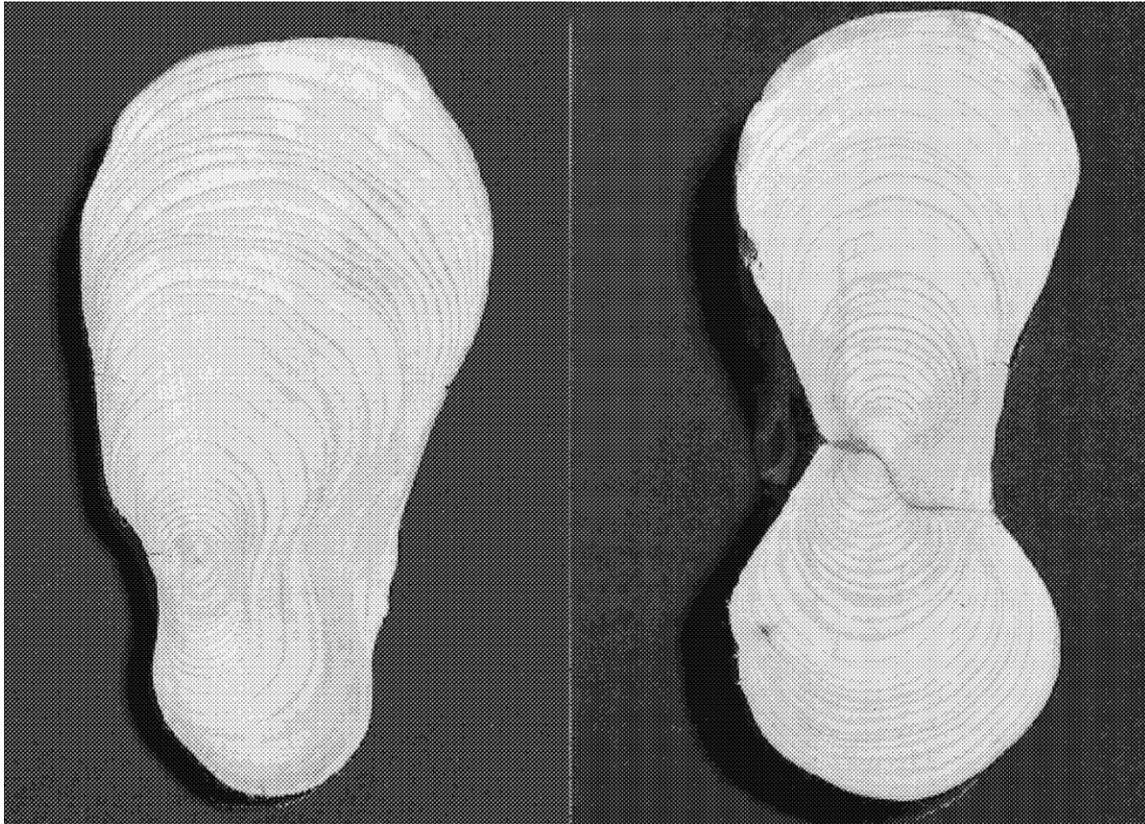


Figure 2: Left: root with T-shape, Right: root with I-shape (Nicoll and Ray, 1996).

2.3 Natural frequency

The frequencies a tree will oscillate with under free vibration are referred to as the natural frequencies. Resonance will occur if a tree is forced at one of these frequencies. The natural frequencies are the frequencies of the normal modes of a system. The mode of vibration is numbered according to the number of half waves that can occur in the vibration. The first normal mode dominates the response of the system in this case the tree. A lot of studies have focused on the natural frequencies of trees (Sugden, 1962), (Mayhead, 1973), (Flesch and Wilson, 1999) (Moore and Maguire, 2004). Previous research showed that to understand the behaviour of trees it is necessary to not only analyse the static behaviour, but also analyse the dynamic behaviour of trees. Because trees are dynamic systems their reaction will vary over time. The frequency response of a tree is mostly depending on wind gusts with a frequency close to the natural frequency of a tree (Gardiner, 1992).

Research is performed to relate the natural frequency to architectural parameters of the tree, such as the diameter at breast height (DBH), the height, the mass etc. Several relationships have been found, the following relation is based on modelling a tree as weightless beam with a top load (Mayhead, 1973).

$$T = 0.86 + 0.74 \frac{H\sqrt{MH}}{DBH^2} \quad (1)$$

Where H = total tree height (m), M = tree mass (kg) and T = sway period, the frequency = 1/T.

The following, even easier, relation is based on a beam with a distributed weight as model. This relationship is tested on 602 trees from eight different species (Gardiner, 1992) and is presented in equation (2). The frequency is linearly related to the ratio of the diameter at breast height divided by the height of tree squared.

$$f = b_1 \frac{DBH}{H^2} \quad (2)$$

These kind of relations can give a good estimate of the natural frequency of a tree but it is not possible to detected small changes in frequency due to weight changes with these relations. These relations are more often used to compare measurements obtained on different.

Milne (1991) and Gardiner (1992) showed that the frequency of the tree increased when the branches were removed, their data is presented in Figure 3 against the DBH/H^2 on the x-axis. The effect of snow load on a tree also showed a change in frequency when no snow was presented the frequency increased with approximately 30% (Papesch, 1984). The increases in frequency did not appear to be due to changes in damping ratio but can be explained by the reduction in mass of the tree (Moore and Maguire, 2005).

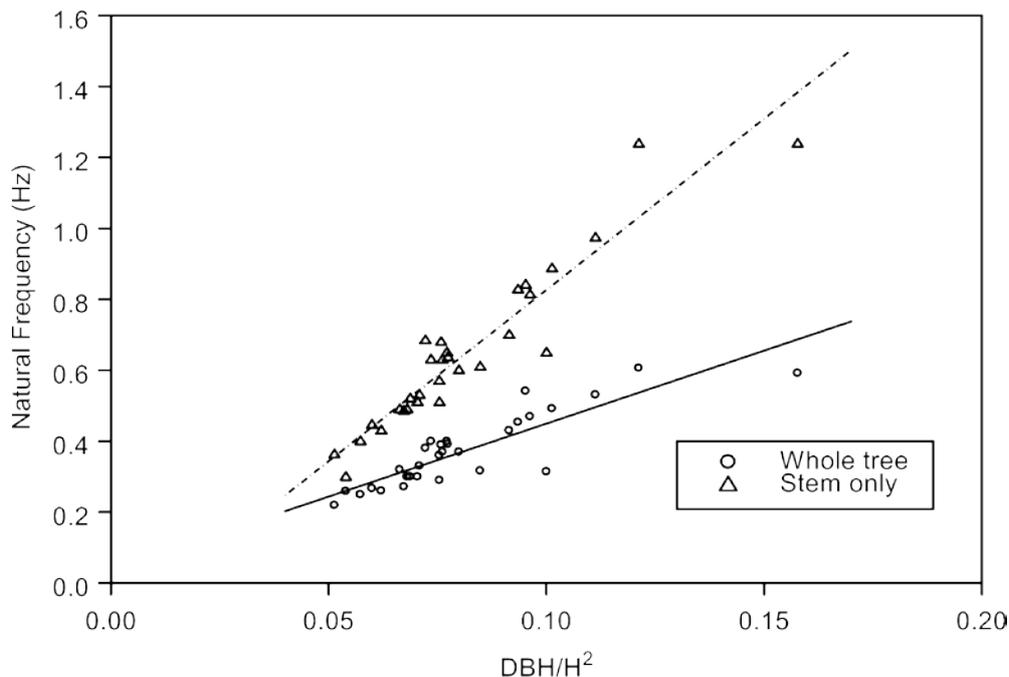


Figure 3: Comparison natural frequency of a tree with and without branches (Moore and Maguire, 2004).

2.4 Commonly used measurement methods

There are two main methods which have been used often in previous studies to analyse the dynamic reaction of a tree, the free sway-method and the wind-method. For the sway-method the tree is brought out of its gravitational centre and subsequently the tree is released to let it sway freely. This is a short duration measurement. The wind-method, as the name already implies, measures tree movement under windy conditions. The energy input is the biggest difference between these two methods. With the sway-method the tree is pulled at one point and the energy is stored in the bending of the tree trunk which then is suddenly released. In natural conditions this will never happens. During the wind-method the wind will push on the whole tree canopy, the energy is delivered in a pulsating way over long periods of time (James et al., 2006).

Several devices are used to measure the oscillations of trees the most used ones are displacement transducers (Friesen et al., 2013). Other methods used are video-based techniques, prism-based measurements and accelerometer based measurements. The prism-based measurement was developed for marksmanship training and makes use of an infrared emitter and an optical controller. The accelerometers are now a days used for wide range of goals. The downside of accelerometers for the use of measuring tree oscillations is that it is necessary to transfer from acceleration to displacement. This is done by calculating the double integral of the measured data but for this initial position of the tree is necessary. Any error in the initial position is aggravated by taken the double integral also known as zero-drift. This easily can lead to an error in displacement of a dozen of meters (Hassinen et al., 1998).

2.5 Models used to describe the dynamic behaviour of trees

Modelling the dynamics of a tree is based on understanding the influences of different elements of a tree to the dynamical behaviour. The root system, the shape, the mechanical characteristics of the trunk and the branches will all have influence on the tree dynamics. The interaction between these different elements will determine the total dynamical behaviour (Brüchert and Gardiner, 2006). Most studies conclude that trees are behaving like damped harmonic oscillators. The energy from swaying is dissipated by different sources, crown clashing of different trees takes account for 50% and aerodynamic damping accounts for 40% of the damping. Structural damping only accounts for 10% of the damping (Milne, 1991).

The branches of a tree have a big influence on the dynamics of tree sway in the wind. When the branch mass increases compared to the trunk mass the natural frequency of the trunk becomes less important. The branches will damp the whole tree. This indicates that trees with different crown structures need to be modelled with different models (James et al., 2006). This also indicates that sway is not a harmonic movement but a very complex movement due to the dynamic interaction of branches. Each branch acts like a mass that swings separately in the wind and interacts with other branches and the stem. The interaction between the branches can cause a lot of damping. To fully understand these movements the branches need to be modelled as individual harmonic oscillators coupled to the main stem. Multiple resonance damping is used as a principal to describe the dynamical behaviour (Spatz et al., 2007), (Fournier et al., 1993).

Since a tree is such a complex structure a lot of different model structures have been proposed to describe the dynamic behaviour. Physical models have been used for example a first order spring-mass system (Brüchert and Gardiner, 2006), (Sellier and Fourcaud, 2005). Finite element models also have been applied to get a better understanding of the interaction of the branches of a tree (Sellier et al., 2006), (Moore and Maguire, 2008).

2.6 Use for this research

The mechanical properties of a tree are determined by the forces it endures during its life time. The wind will be a determining factor in the development of the mechanical properties of a tree. This means a tree will be anisotropic and thus have a different frequency in every direction.

Two methods have been mainly used in previous research on the dynamics of trees. These methods will be used in this research as well. To model tree dynamics several different model structures have been used in previous research. In this research the simplest model, a first order damped spring-mass system is used to analyse the data.

3 | Methodology

A new non-destructive continuous method to determine the fluctuations in natural frequency of trees is developed during this research. The accelerations of a tree are measured in three directions with an accelerometer. The tree is modelled as a damped first order spring-mass system. The experiments are performed with two different driving forces. For the first method the input force is delivered as a single pulse input, this is called a sway test. For the second method the wind is used as driving force. The sway tests are analysed in the time and frequency domain, the wind experiments are analysed in the frequency domain. Before testing on a tree the sway and wind experiments are performed on a stick to test the method. Subsequently the experiments are repeated with different amount of weights attached to the stick/tree.

3.1 Accelerometer

An accelerometer measures the physical acceleration which is experienced by the accelerometer or the object to which it is attached. When an accelerometer is at rest on earth it will measure the gravitational constant g of $9,81\text{m/s}^2$ due to its own weight. When an accelerometer is in free fall it will measure zero. The way an accelerometer measures acceleration is by measuring the displacement of a small weight which is attached to a spring (Lee et al., 2005). This displacement is then converted to an electrical signal. The electrical signals are saved with an data logger. In this research all the accelerations are given in g -force a common unit when measuring with accelerometers. The accelerometers used in this research are data loggers from 'Gulf Coast Data Concepts' (model: X6-1A) see Figure 4. For the preferences of this accelerometer see Appendix A |Accelerometer.



Figure 4: Accelerometer used during this research.

Accuracy

The settings of the accelerometer used in this research are an acceleration range of $\pm 2\text{ G}$, 160 Hz sample rate and a 16-bit resolution. This means the acceleration is measured with a step size of:

$$\text{step size} = \frac{\text{range}}{2^{\text{bit}}} = \frac{4}{2^{16}} = 6.1 \cdot 10^{-5} [\text{G}]$$

Time stamp

The data logger saved a timestamp for each measurement. The problem with the accelerometers used during this research is that the time interval is not constant. A solution for this problem is to interpolate the data with a constant time axis.

3.2 Control experiment

The control experiment is performed on a wooden stick which is referred to as the simplified system. The dimensions of the stick are $88 \times 2.5 \times 0.5$ cm ($l \times b \times h$) and a weight of 94 grams. An accelerometer is attached to the top of the stick. To perform the experiment the stick is fixed in a vice. To let the stick vibrate, the stick is brought out of its equilibrium and released. For the wind experiment the stick is left outside in the wind. This stick is chosen because it has only one dominant vibration direction, this is caused by the dimensions of the stick. The stick vibrates with approximately the same frequency as a small tree, this is around 1Hz. A weight has been added to the top of the stick to analyse the relation between the frequency and the weight. All the weight is added in the top of the stick. The amount of weight has been changed between the minimum weight of 250 grams and a maximum weight of 750 grams to analyse the effect on the frequency. This is an increase in weight of 700% compared to the own weight of the stick. The experiment setup is shown in Figure 5.



Figure 5: Left: The set up for the wind experiments on a stick and a tree, right: sway experiment setup.

3.3 Tree experiment

Measurements are performed on different trees during this research. The accelerometer is attached to the tree trunk just below the start of the crown. This location is chosen because the higher the accelerometer is attached, the larger the displacement of the tree. The accelerometer is not attached in the top of the crown because this research is interested in the vibration of the total tree and not the frequency of a single branch in the top of the crown. The trees used for this research are standing in the 'Mekelpark' at the Technical University of Delft. The research is performed on relatively small trees (height ≈ 6 m, perimeter ≈ 0.29 m). An example of the experiment set up is shown in Figure 5.

The small trees are brought in vibration with a single pulse input. The tree was pulled out of its equilibrium and released by pushing against it. For bigger trees a different method is developed. This method is explained in Appendix C |Sway method. To analyse the relation between weight and frequency different amount of weights were added in the tree during this experiment. The weights are added as point weights at the start of the crown.

For the wind experiments the accelerometers are attached to the tree. During the experiment every two hours a new weight was added (0, 8 and 12kg). To check if variations in the frequency were not caused by other changing factors for example changes in wind, another accelerometer was attached to a 'control' tree close by, no weight was added to this tree.

3.3.1 Weight estimation

The total weight of the tree is calculated in a very rough way. For this research a rough estimate is good enough. The weight is estimated just to show that the added weight during the experiments is in the right order of magnitude in comparison with the expected changes in moisture content of a tree. The formula presented in equation (3) is based on a research on 116 trees from 9 different species (Murray, 1927). Of course this is still a rough estimation.

$$W \approx 7.08 C^{2.49} \quad (3)$$

Where:

W is weight in grams

C is the maximum stem circumference in cm

With a circumference of 29 cm this formula gives a weight of 31 kg. The maximum weight added during this research is 40% of the own weight of the tree.

3.4 Model time domain

The obtained data are accelerations in g-force. These accelerations will be used to find the natural frequency. The natural frequency is a function of the stiffness and mass (equation (5)). The tree is modelled as a damped first order spring-mass system see equation (4). The model will be used to find the natural frequency. This simple description is used in earlier research to model frequency of trees. The displacement of a damped spring-mass system is modelled with equation (4).

$$z(t) = Ae^{-\zeta\omega_0 t} \sin(\sqrt{1 - \zeta^2}\omega_0 t + \varphi) \quad (4)$$

Where

$z(t)$ = deviation from resting position

A = amplitude impulse

ζ = damping ratio

φ = initial phase

ω_0 = undamped natural frequency=eigen frequency

k = spring stiffness

m = mass

Where the undamped natural frequency is given by

$$\omega_0 = \sqrt{k/m} \quad (5)$$

And the damping is given by

$$\zeta = \frac{c}{2m\omega_0} \quad (6)$$

The observed frequency by the accelerometer will be slightly lower than the natural frequency. The natural frequency can be calculated out of the observed frequency with equation (7).

$$\omega_1 = \omega_0 \sqrt{1 - \zeta^2} \quad (7)$$

The output of the model described in equation (4) is presented in Figure 6. The following parameters were used; a frequency of 1Hz, a damping ratio of 0.02, a gain of 0.1 and an initial phase of 1.

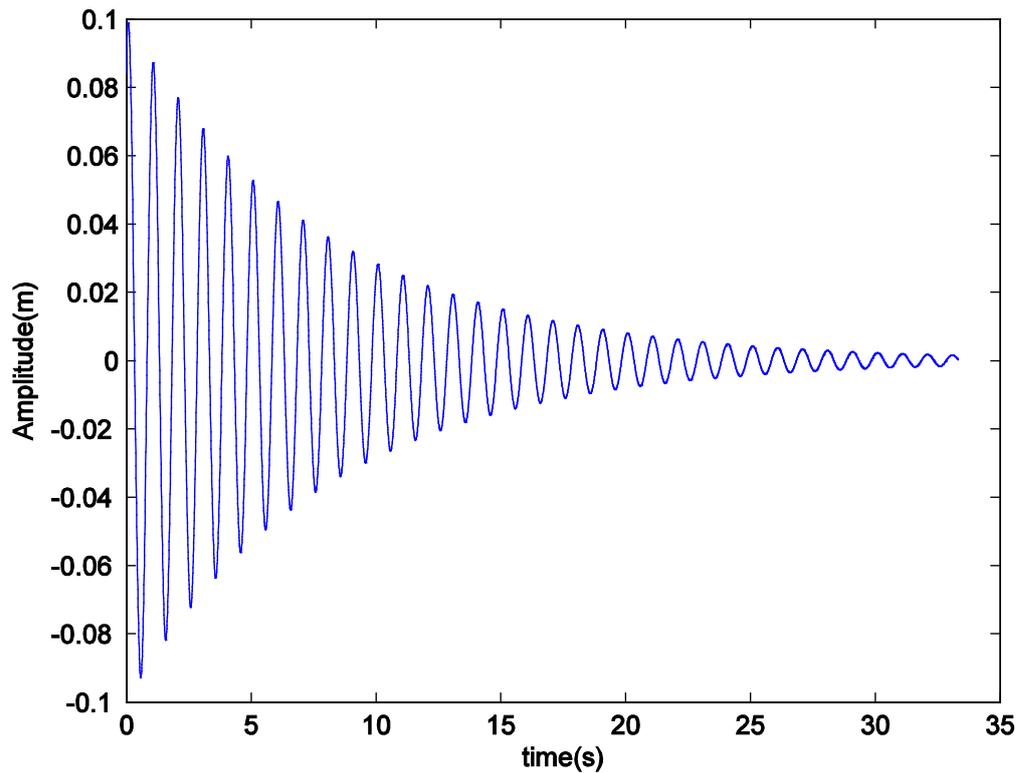


Figure 6: Output of the model described in equation (4), with a frequency of 1Hz.

3.4.1 Accelerations or displacement

With this model the displacement can be calculated, but with the accelerometer acceleration is measured. The acceleration is the second derivative of the displacement. The derivation of the second derivative of this model is presented in derivation (8).

$$\begin{aligned}
 z(t) &= Ae^{-\zeta\omega_0 t} \sin(\sqrt{1-\zeta^2}\omega_0 t + \phi) \\
 z'(t) &= -\zeta\omega_0 Ae^{-\zeta\omega_0 t} \sin(\sqrt{1-\zeta^2}\omega_0 t + \phi) + Ae^{-\zeta\omega_0 t} \cos(\sqrt{1-\zeta^2}\omega_0 t + \phi)\sqrt{1-\zeta^2}\omega_0 \\
 z''(t) &= \zeta^2\omega_0^2 Ae^{-\zeta\omega_0 t} \sin(\sqrt{1-\zeta^2}\omega_0 t + \phi) - \zeta\omega_0 Ae^{-\zeta\omega_0 t} \cos(\sqrt{1-\zeta^2}\omega_0 t + \phi)\sqrt{1-\zeta^2}\omega_0 \\
 &\quad - \zeta\omega_0 Ae^{-\zeta\omega_0 t} \cos(\sqrt{1-\zeta^2}\omega_0 t + \phi)\sqrt{1-\zeta^2}\omega_0 - Ae^{-\zeta\omega_0 t} \sin(\sqrt{1-\zeta^2}\omega_0 t + \phi)(\sqrt{1-\zeta^2}\omega_0)^2
 \end{aligned} \tag{8}$$

With $P = \sqrt{1-\zeta^2}\omega_0$ & $Q = \zeta\omega_0$

$$\begin{aligned}
 z''(t) &= Q^2 Ae^{-\alpha t} \sin(Pt + \phi) - QPAe^{-\alpha t} \cos(Pt + \phi) - QPAe^{-\alpha t} \cos(Pt + \phi) - AP^2 e^{-\alpha t} \sin(Pt + \phi) \\
 z''(t) &= Q^2 Ae^{-\alpha t} \sin(Pt + \phi) - 2QPAe^{-\alpha t} \sin(Pt + (\phi - \frac{1}{2}\pi)) - AP^2 e^{-\alpha t} \sin(Pt + \phi)
 \end{aligned}$$

In this research it is decided to work with accelerations instead of displacement, because the acceleration is measured with the accelerometers. For the conversion from accelerations to displacement the initial starting position is required any inaccuracy in this will be amplified by integrating twice. This problem is called 'zero' drift. The formula for the displacement of a damped first order spring-mass system is used to calculate the acceleration. The formula for the acceleration of a first order spring-mass system shows that the natural frequency is the same as in the formula for the displacement. The amplitude is different but since this research is only interested in the frequency this doesn't matter.

3.5 Model Sensitivity

For a damped spring-mass system the mass is inversely related to the frequency as is shown in equation (5). For small increases or decreases of the mass the increase or decrease of the natural frequency will be half the percentage in the other direction (see derivation (9)).

$$\begin{aligned}
 \omega_0^o &= \sqrt{\frac{k}{m}} \\
 m' &= \alpha m \rightarrow \alpha \{0.9 - 1.1\} \\
 \omega_0^n &= \sqrt{\frac{k}{\alpha m}} = \sqrt{\frac{1}{\alpha}} \sqrt{\frac{k}{m}} = \sqrt{\frac{1}{\alpha}} \omega_0^o \\
 \frac{\omega_0^n}{\omega_0^o} &= \sqrt{\frac{1}{\alpha}} = \alpha^{-0.5} \\
 \frac{d \omega_0^n}{d \alpha} &= -0.5 \alpha^{-1.5}
 \end{aligned} \tag{9}$$

3.5.1 Indication of the necessary accuracy

The expected water content variation is maximal 20% of the total weight of the tree. This means a maximum decrease of 8.7% in frequency. Let's assume that to measure a variation in water content, at least 9 steps have to be measured between the minimum water content and the maximum water content. This means the spread in data for a constant weight has to fall within a range of 1% of the frequency.

3.6 Frequency domain

The wind is a noisy unknown input to this system which will make the measured signal a convolution of equation (4). It is not possible to fit this measured signal to the model proposed for the time domain. It is possible though to analyse the measured data in the frequency domain. The frequency spectrum of the wind is a power function (Hwang, 1970). The measured data is a combination of the frequency spectrum of the wind, and the frequency spectrum of the system. To get the total frequency spectrum, in other words the measured data, these two spectrums have to be multiplied (Lathi, 1998).

To examine the measured data in the frequency domain the Fourier transform is taken. Every function can be written as a sum of simple waves (sines and cosines). The Fourier transform is a decomposition of a signal into sinusoids of different frequencies. The magnitude at the different frequencies represents the amplitude of a frequency component (see Figure 7).

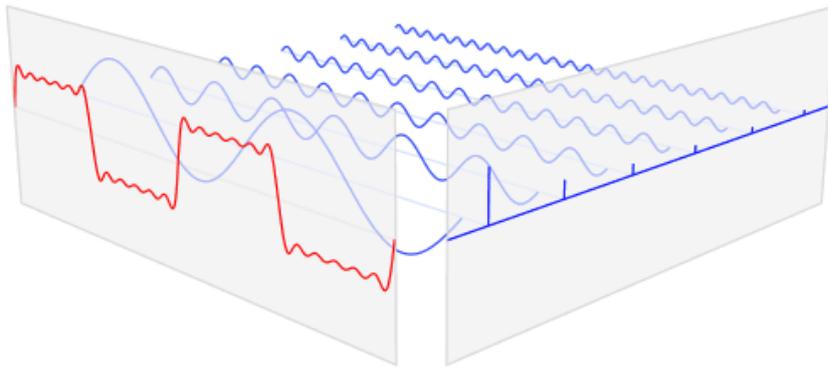


Figure 7: Decomposition of signal into waves (Fourier analysis).

The Fourier transform of equation (4) is given in equation (10). This is the amplitude of the frequency spectrum of the first order spring-mass system.

$$|Z(\omega)| = \frac{1}{\sqrt{(\omega_0^2 - 2\xi^2 - \omega^2)^2 + 4\xi^2(\omega_0^2 - \xi^2)}} \quad (10)$$

The frequency spectrum of the wind is unknown, this will be modelled as an extra unknown parameter ω_w . Which leads to the model for the measured frequency spectrum shown in equation (11). This means the frequency spectrum of the wind is modelled as a gain.

$$|H(\omega)| = \omega_w \frac{1}{\sqrt{(\omega_0^2 - 2\xi^2 - \omega^2)^2 + 4\xi^2(\omega_0^2 - \xi^2)}} \quad (11)$$

The Fourier transform will generate complex numbers any complex number z can be rewritten according to equation (12).

$$z = |z|e^{i\text{Arg}(z)} \quad (12)$$

$$\text{Arg}(x + iy) = \arctan(y/x)$$

The output of the model of this system in the frequency domain is presented in Figure 8. The parameters used are a frequency of 1Hz a damping of 0.02 and gain of 0.1.

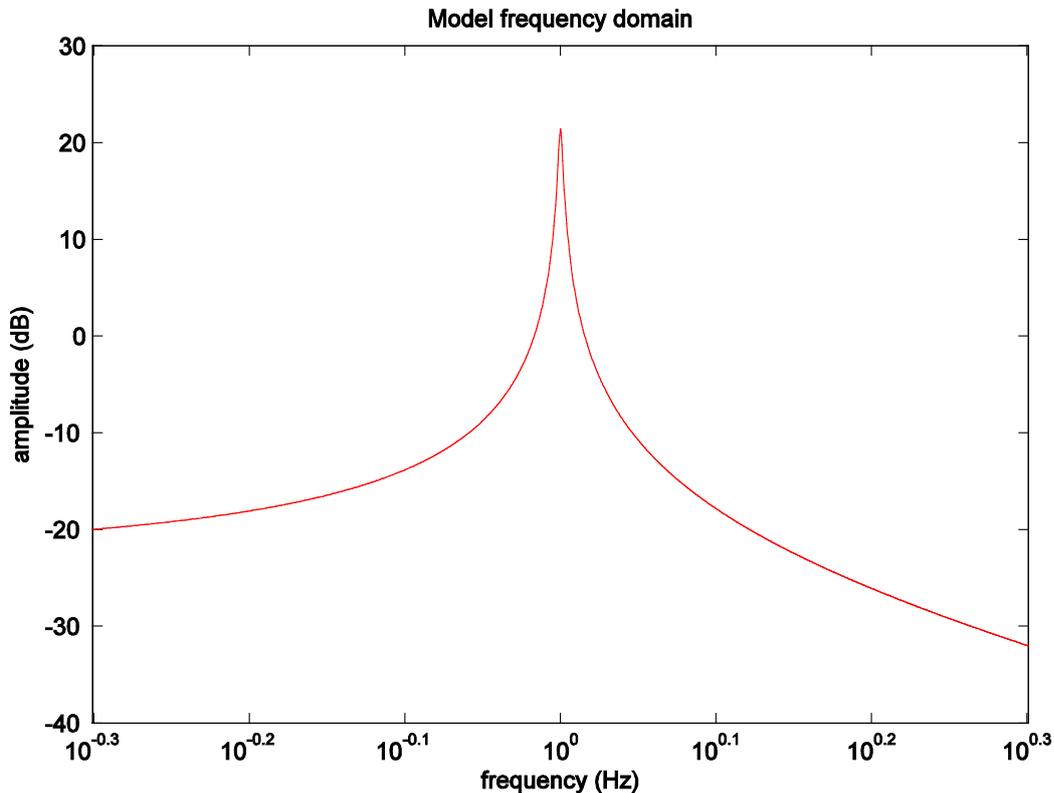


Figure 8: Model output of the spring-mass system in the frequency domain, with a frequency of 1 Hz.

3.6.1 Selected time interval for wind experiments

For the analysis of the wind experiments it is necessary to select a time interval to perform the Fourier transformation on. The size of the interval is arbitrary. The influence of the selected time interval is investigated. Time intervals of 1, 2, 5, 15 and 30 minutes are analysed. A short interval has the advantage that it is possible to measure with a higher measurement density. For this research a 30 minute interval is chosen as the largest interval because this method is developed to analyse diurnal changes.

3.7 Principal component

The accelerometer measures g-forces in three directions. The tree or simplified system does not necessarily vibrate actually in one of these three directions. To overcome this problem a principal component analysis is performed. By doing a principal component analysis the orientation of the axis is changed in such a way that the first principal component has a maximum variance (Jackson, 2005). In this way the data is always analysed in the direction with the highest variance, in the case of this research this will be the direction with the most movement.

The principal component shows the main vibration direction. Since a tree has anisotropic mechanical properties the movement direction of a tree will influence the results. With a principal component analysis it is possible to calculate how much one principal component contributes to the total variance.

3.8 Calibrating parameters

All the measured data is analysed by optimizing the model parameters for a certain data set. For the time domain model the amplitude impulse, natural frequency, initial phase and damping ratio are calibrated. For the frequency domain the natural frequency, the damping ratio and the frequency spectrum of the wind are calibrated. The optimizing of the parameters is done with the matlab function `nlinfit` (Holland and Welsch, 1977). `Nlinfit` minimize the mean squared error residuals.

In the time domain the model is calibrated to one single vibration. Since the MSE is used to calibrate the model the start of the vibration will have more influence than the tail of the vibration because the amplitude of the vibration is higher at the start.

In the frequency domain the model is calibrated on a 'small' window of the frequency domain. This domain is chosen in such a way that the natural frequency of the system is in there, the frequencies outside of this domain are neglected. This is done because the wind spectrum tends to have a high magnitude at the low frequencies. This high magnitude is caused by measuring accelerations instead of displacements. When the whole frequency domain is used to calibrate the model, the natural frequency might not be the most sensitive parameter.

4 | Results and discussion

The presented models in chapter 3 | Methodology, are calibrated for the measured data to obtain the natural frequency. First an analysis of the movement direction of the tree during the experiments is presented. This analysis is based on the principal component analysis. Four different kind of tests have been performed for the 'main' movement direction in other words the first principal component. Existing out of two control tests on the simplified system (one in the wind and one sway test) and two tests on a tree (one in the wind and a sway test). For the wind experiments the influence of the amount of time analysed per experiment is investigated. During the further analysis for all the wind experiments a 15 minute interval is used.

4.1 Movement direction

As explained in chapter 2 | a tree has anisotropic mechanical characteristics. An analysis of the movement direction of the tree during the different experiments has been done. In Figure 9 a top view of the movement of a tree during a sway experiment is presented. The first and the second principal components are displayed. In this case the first principal component captures 97% of the variability and the second principal component captures 3%. The third principal component, which is not shown, only captures a very small part of the variability, which makes sense because the tree trunk is not moving up or down. It is clearly visible that the vibration direction of the tree changes slightly during the total vibration.

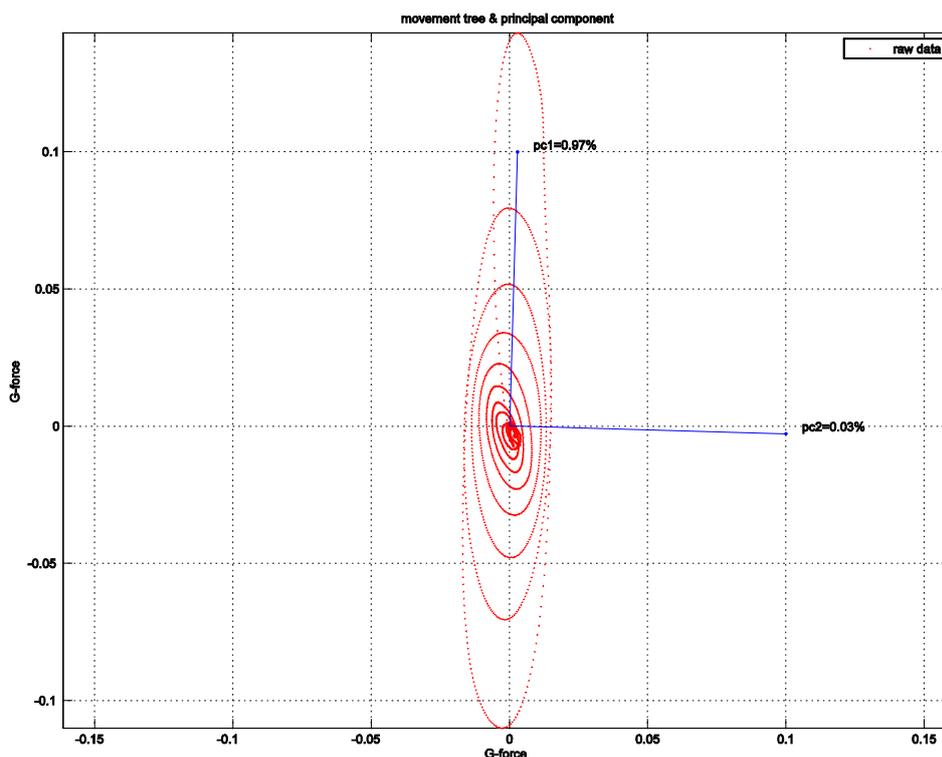


Figure 9: Movement of tree as a top view in red, the movement direction is changing during the vibration. The first and second principal component in blue.

The angle of the 'main' vibration direction (first principal component) of all the experiments is presented in Figure 10. The blue lines are the main directions of the sway experiments and the red lines are the main directions of the wind experiment. The tree is moving to the other side of the origin as well, but since the direction is of interest here this is not shown.

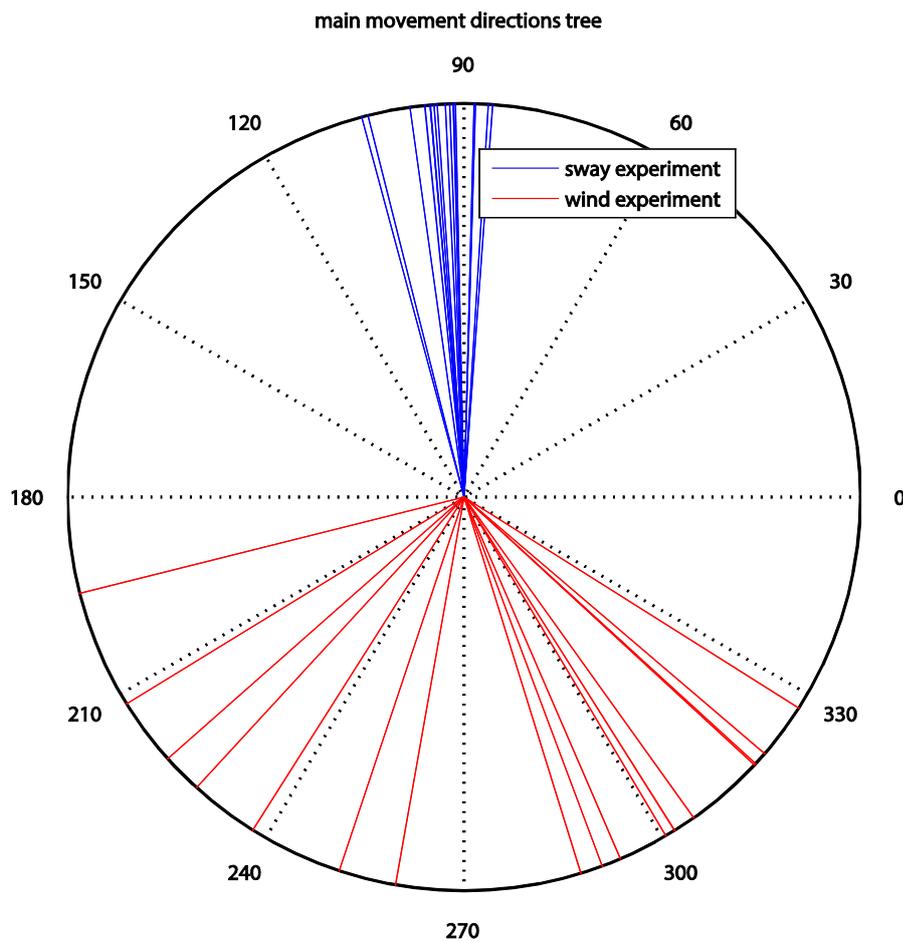


Figure 10: Main vibration direction (first principal component) for the wind experiments in red and the sway experiments in blue. The vibration direction of the wind experiments is varying more than the movement direction of the sway experiments.

During the sway experiments the tree swings more or less in the same direction (a range of 0.3 rad), this is due to the way the experiment is performed. The tree is pulled and released in the same direction every single experiment. This is done to reduce the influence of the anisotropy of a tree. During the wind experiment the tree is moving in all directions even during one single experiment the tree is moving in several directions. The tree more or less moves in circles. This means the first principal component will, on average, only capture 60% of the total variance. For the sway experiment the first principal component captures 97% of the movement. In this research the first principal component is still used to model the frequency for both the sway and the wind experiments. In Table 1 an overview of all the different experiments is given. The direction of the first principal component is given as an angle. The contribution of the first principal component to the total variance is presented as a percentage. The modelled frequencies in the frequency domain are also presented. Further on in this chapter an analyses of the modelled frequencies is presented. The parameters are presented for the sway and the wind experiments. Every single wind experiment is based on a 15 minute time interval.

Table 1: Overview of the direction in radians, the contribution to the variance as a percentage and the modelled frequency in Hertz of the first principal component.

experiment	sway experiment			kg	wind experiment		
	angle [rad]	%	Hz		angle [rad]	%	Hz
1	1.50	0.91	0.855	0	2.38	0.67	0.888
2	1.83	0.95	0.817	0	1.78	0.54	0.896
3	1.55	0.96	0.823	0	2.46	0.61	0.902
4	1.71	0.98	0.794	0	1.01	0.52	0.861
5	1.65	0.99	0.800	0	2.40	0.54	0.856
6	1.60	0.99	0.815	8	2.43	0.58	0.855
7	1.61	0.97	0.812	8	2.39	0.63	0.877
8	1.60	0.99	0.810	8	2.19	0.71	0.846
9	1.62	0.98	0.799	8	1.93	0.59	0.876
10	1.64	0.99	0.817	8	2.11	0.66	0.829
11	1.54	0.97	0.784	12	2.13	0.71	0.851
12	1.51	0.89	0.777	12	0.55	0.59	0.791
13	1.66	0.99	0.782	12	0.73	0.60	0.812
14	1.67	0.97	0.774	12	1.40	0.59	0.846
15	1.59	0.99	0.789	12	1.25	0.58	0.843
16	1.82	0.98	0.780	12	0.83	0.65	0.823
17	1.66	0.99	0.782	12	2.58	0.68	0.809

There is no relation observed between the percentage of the variance captured by the first principal component and the accuracy of the modelled frequency. These two parameters are presented in Figure 11 where the median is drawn as a red line. For the higher percentages of variance captured with the first principal component the frequencies are not closer to the median.

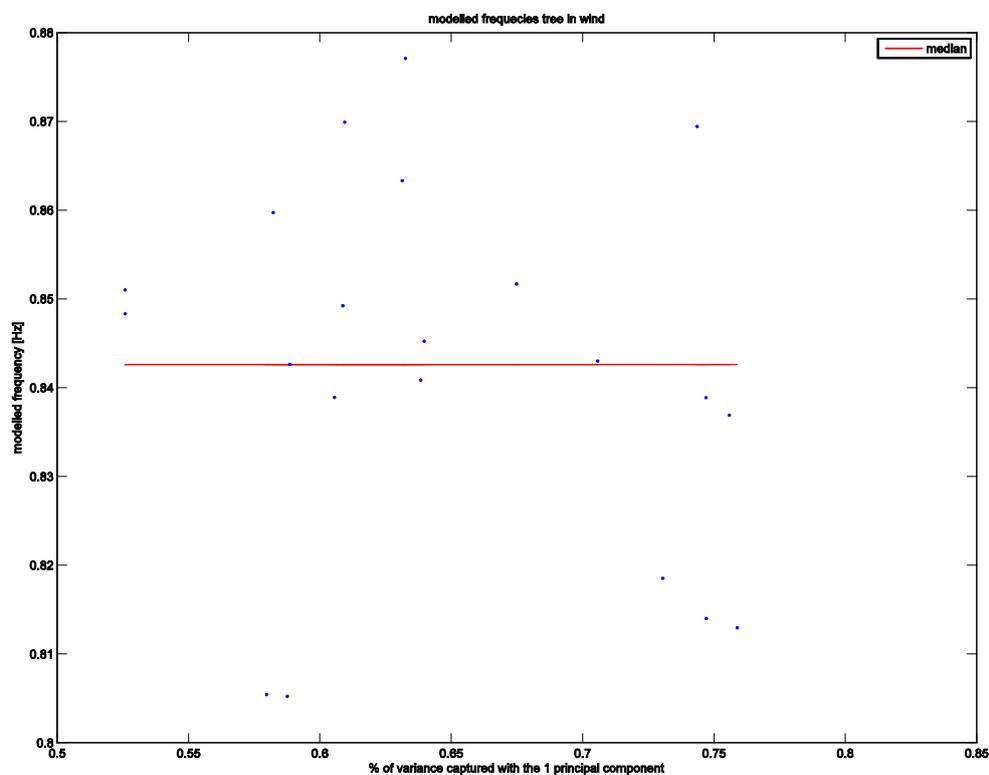


Figure 11: Modelled frequency compared with percentage of variance captured with the first principal component. There is no correlation between the percentage and the natural frequency.

The movement directions for the wind experiment presented in Figure 10 are the directions of the principal components, analysing 15 minute time intervals for different weights. This data is compared with the tree without added weight, the movement directions of the tree without weight shows a smaller variation in movement direction and a higher percentage of the variance is captured with the first principal component (on average 63%). This can be due to the fact that it is a different tree, which will react different on a certain wind conditions. Another reason might be that the movement direction of the tree with added weight changes because of the added weight. This is very well possible because the weights added were attached to the trunk just above the first branch which means they were not exactly positioned in the centre of the tree. The movement directions per different weight were analysed a slight clustering is observed but the relation is not that clear. The figures of this comparison are presented in Appendix D | Figures.

4.2 Control experiments

The control experiment is performed with a stick. For the simplified system the movement direction is exactly the same for every experiment. The movement direction during one experiment don't change either. This means the percentage captured by the first principal component is very high (on average, 99,9%). It doesn't matter if the data is analysed in the direction of the first principal component or in the z-direction. Because both directions are the same.

4.2.1 Sway experiment

In Figure 12 a vibration of a free sway test is shown this vibration is given in blue. In red the model proposed in Equation (4) is calibrated for the measured vibration. The modelled natural frequency is 0.81Hz. The model is a good is a good description of this vibration.

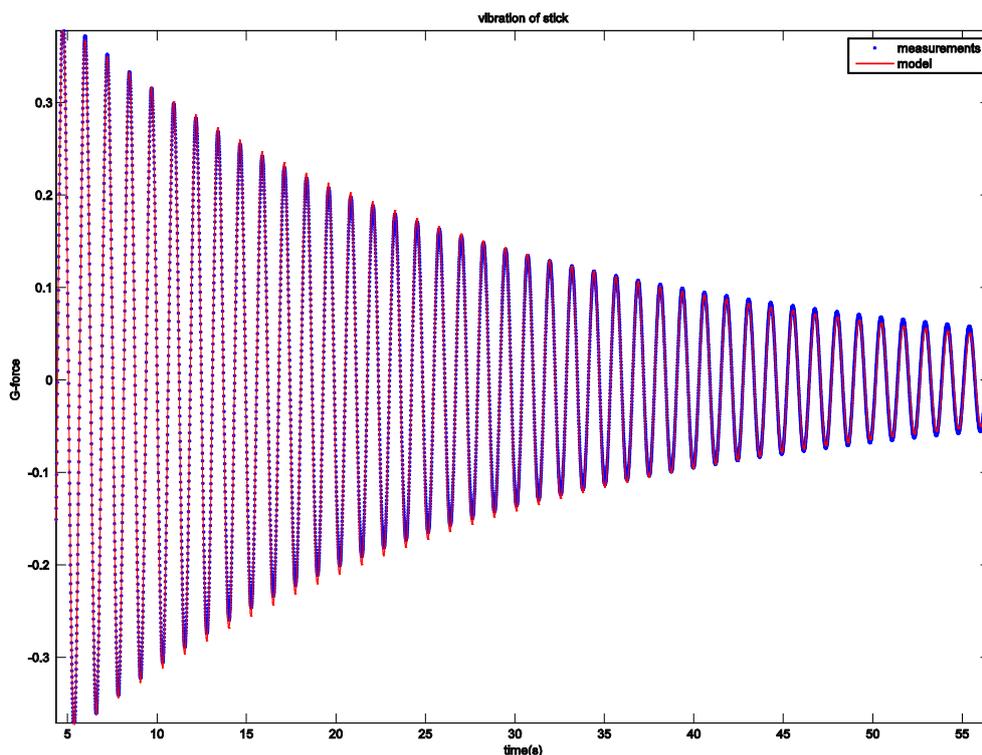


Figure 12: Sway test for a stick with in red the calibrated model. The modelled frequency is 0.81 Hz, the model used is a good description for this vibration.

The same vibration as presented in Figure 12 is analysed in the frequency domain see Figure 13. A very clear peak is observed. The model proposed in Equation (11) is optimized for this vibration (see the red line). The modelled natural frequency is 0.81Hz. Again the model is a good description for the measured data.

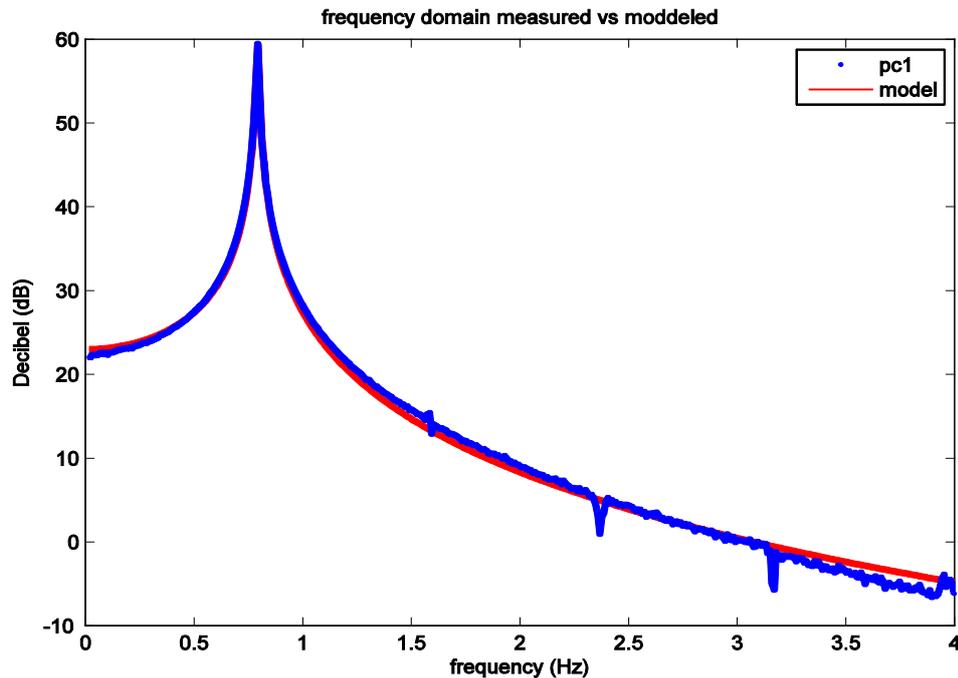


Figure 13: Frequency domain of a stick moving in the wind, with the model plotted as a red line. The modelled natural frequency is 0.81 Hz. The model used is a good description of the data.

The experiment is repeated several times with different weights attached to the top of the stick. The modelled frequencies are presented in Figure 14. Each experiment is repeated several times with the same amount of weight, this is not visible because the modelled frequencies for the same amount of weight are almost the same. The relation between the weight, frequency and stiffness presented in equation (5) is calibrated for these five points. The stiffness modelled is 0.59 N/m and the mean squared normalized error is 0.0067.

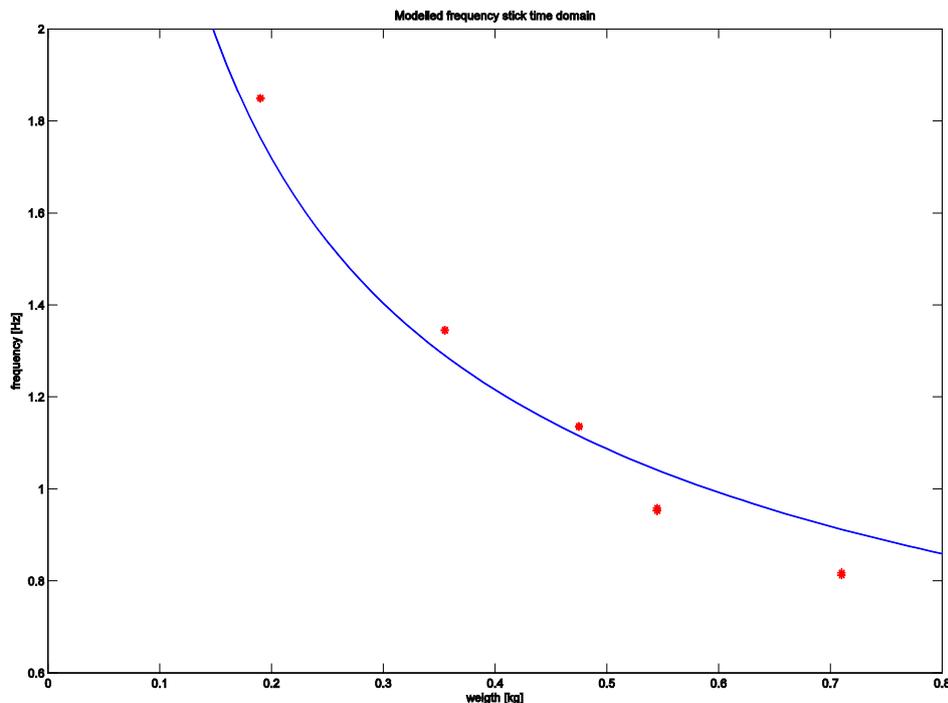


Figure 14: In red the modelled frequency of a stick with different weights. In bleu the calibrated relation between mass, stiffness and frequency presented in equation (5).

4.2.2 Wind experiment

The frequency domain of the simplified system in the wind is presented in Figure 15. The model proposed in Equation (11) is calibrated for this data and presented as a red line. The modelled natural frequency during this calibration is 1.48 Hz. The data presented is from a 15 minute interval.

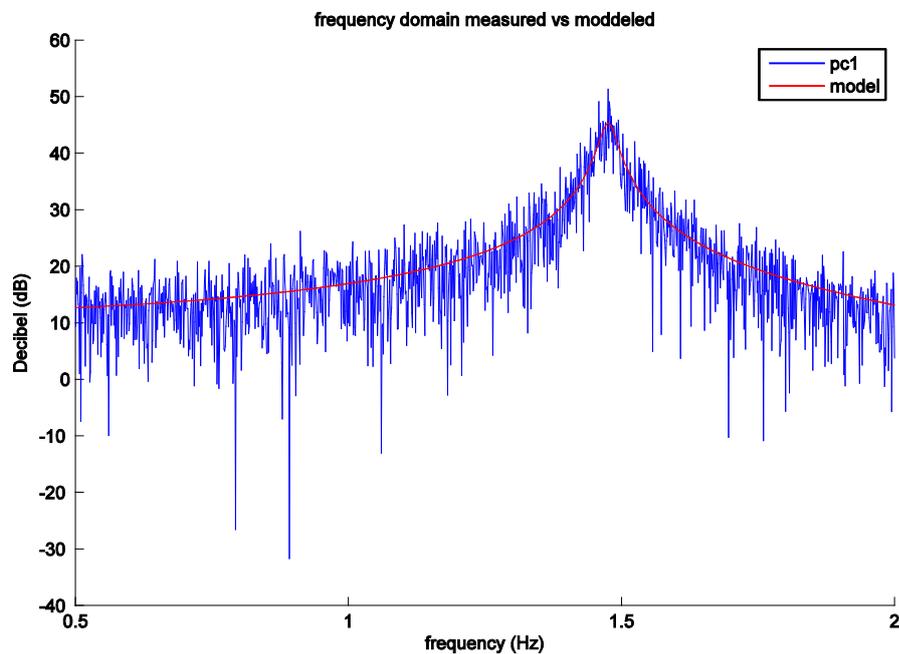


Figure 15: Frequency domain of stick in wind with the calibrated model in red. A natural frequency of 1.48 Hz was modelled.

In Figure 16 the frequencies modelled during the wind experiments are presented for three different weights attached to the stick. There are two remarkable points, 14 and 15, these points were measured during a time interval when there was almost no wind. This shows the results will get less precise when the amount of wind is dropping. For the movement profile of these time intervals see Appendix D | Figures the drop in wind speed is clearly visible in this figure.

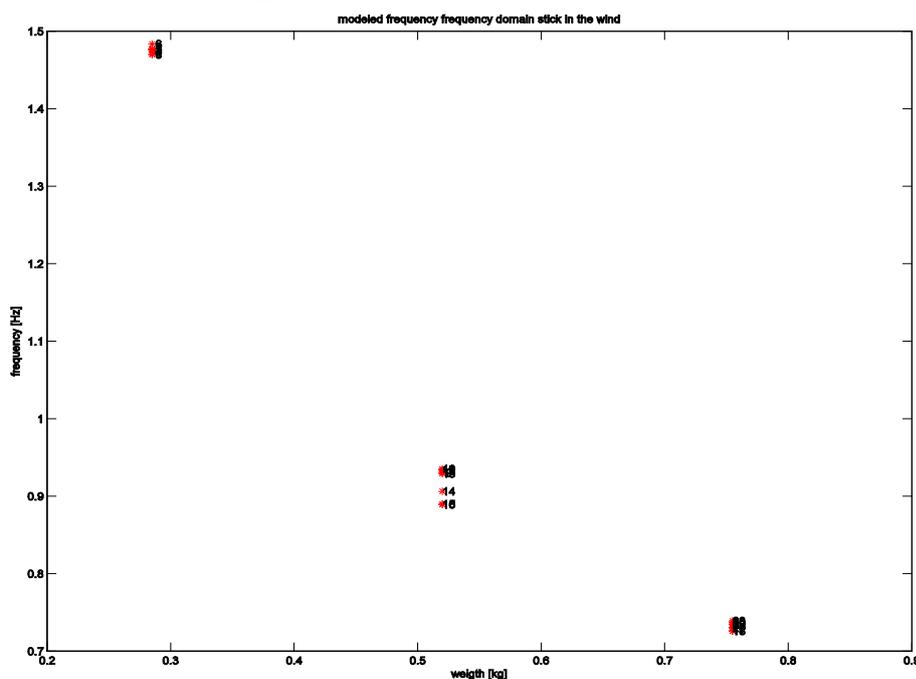


Figure 16: Modelled frequency of stick in the wind. With two outlying points (14 and 15) when there was less wind.

4.2.3 Comparison

The frequencies modelled during the wind and sway experiments are presented in Figure 17. For the sway experiment (bleu) a constant lower value is modelled. It is possible that this has to do with the input energy delivered by pulling on the stick. The spread in measured frequencies per weight falls in a range of 0.015Hz.

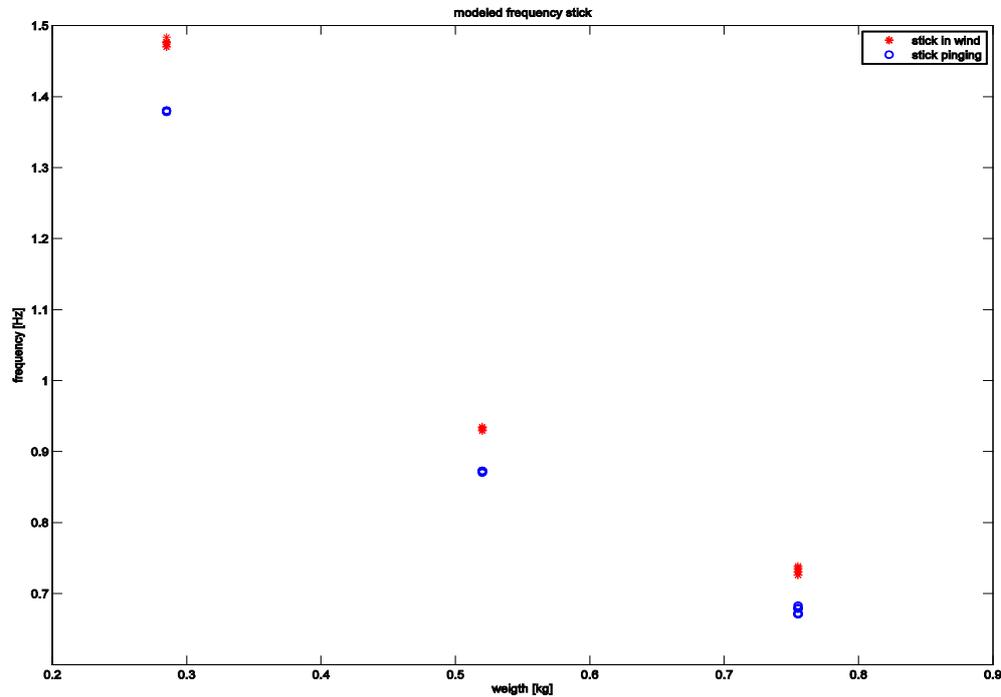


Figure 17: Modelled frequency in frequency domain wind experiment compared with sway test. The values modelled for the sway experiments are constantly lower than the values modelled for the wind experiment.

4.3 Tree

The experiments on the tree are performed in the wind and as sway tests. During both experiments weight is added to analyse the influence of changing weight on the frequency.

4.3.1 Sway experiment

The result of a sway experiment performed on a tree is presented in Figure 18. The natural frequency modelled is 0.81 Hz. At the end of the vibration the model starts to differ from the measured signal. Probably the force to initiate the vibration of the tree has more influence at the start of the vibration than at the end. This can cause the change in frequency observed during this vibration. During this study the MSE is used to optimize the parameters which means the start of the vibration will have more influence on the parameters than the end. An analysis of the instantaneous frequency is performed to check if this would deliver better results. The instantaneous frequency describes a changing frequency over time. The instantaneous frequency didn't deliver better results, the way the instantaneous frequency is calculated is shown in Appendix B | Instantaneous frequency.

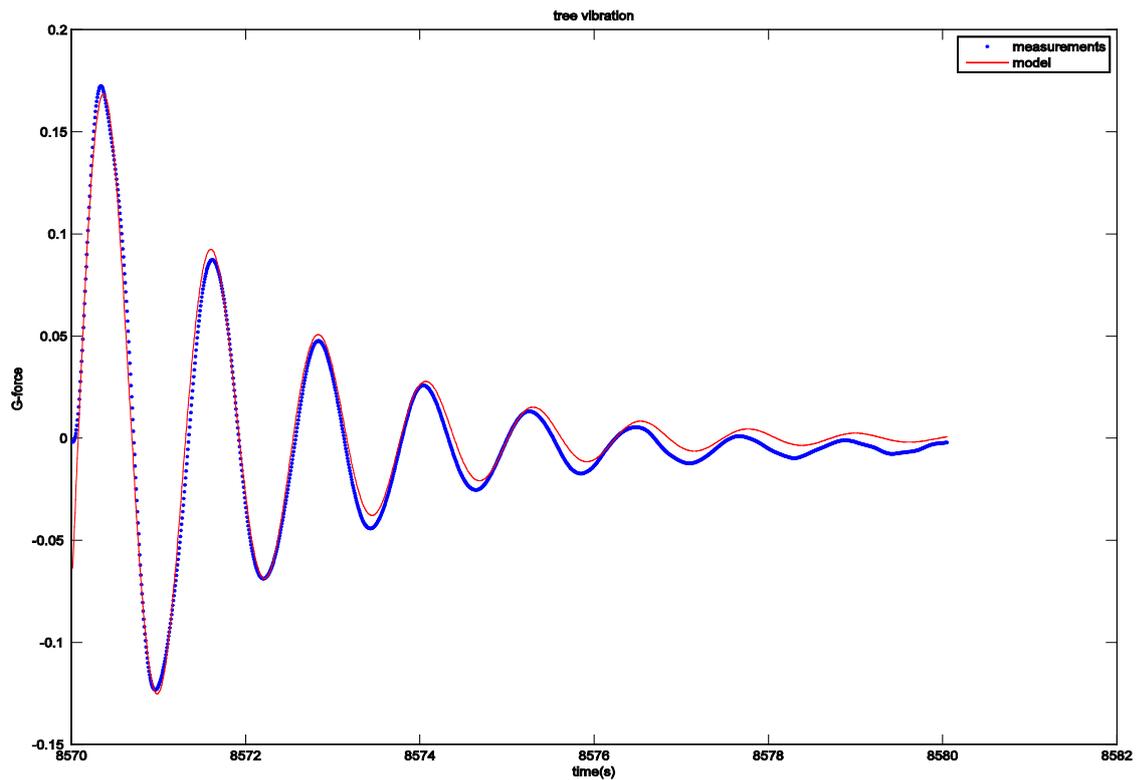


Figure 18: Sway experiment on tree, with in red the fitted model. At the end of the vibration the model and the measurements start to differ.

4.3.2 Wind experiment

A frequency domain of a tree which is moving in the wind for 15 minutes is presented in Figure 19. A clear peak is visible around 0.8 Hz.

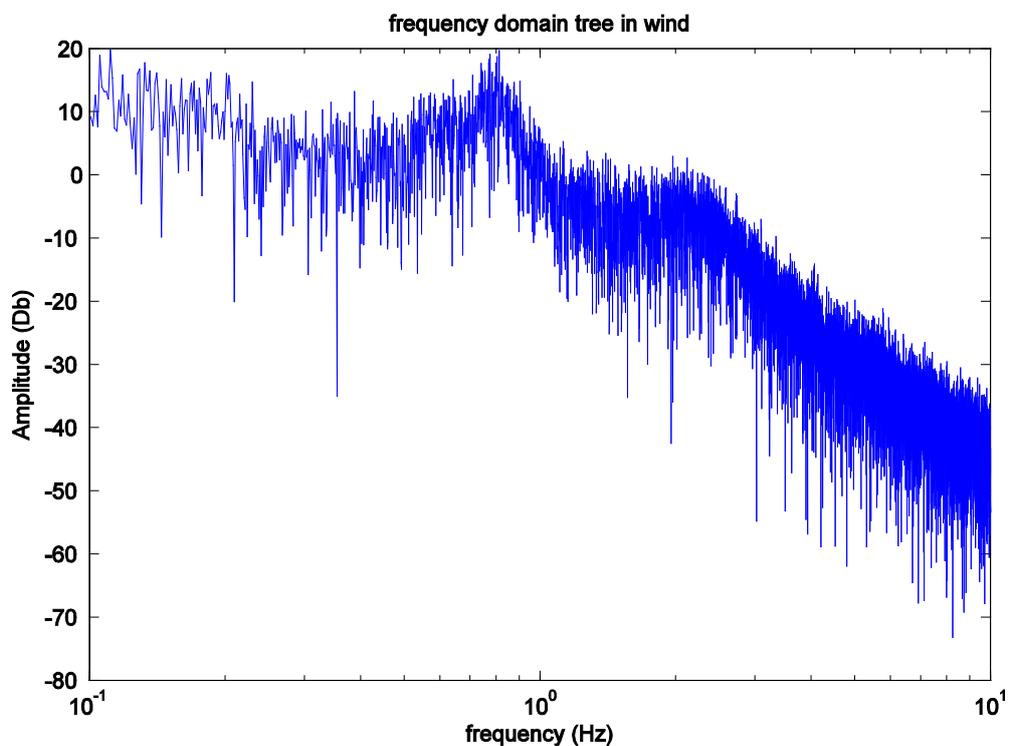


Figure 19: Frequency domain of a tree in the wind for 15 minutes. A clear peak is visible at the natural frequency.

The model is calibrated on a smaller window of this frequency domain from 0.5 Hz to 2 Hz see Figure 20. The modelled natural frequency = 0.79Hz.

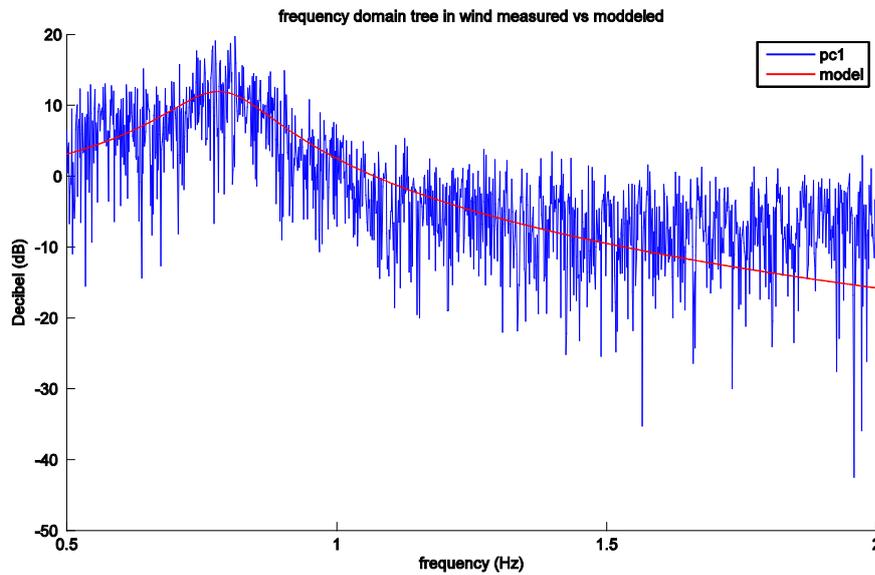


Figure 20: Frequency domain of the tree with the model presented in red. A natural frequency of 0.79Hz was modelled.

4.3.3 Comparison

The modelled frequencies for the sway and wind experiments are presented in Figure 21. It is possible to detect a trend in frequency change with varying weight, but the difference is minimal. The spread in frequencies modelled for each separate weight is around 0.075 Hz. This is a small range but the change in frequency with an increase of weight is of a smaller magnitude. The frequencies modelled with the sway experiment are consequently below the frequencies modelled with the wind experiments. This is also observed with the control experiment.

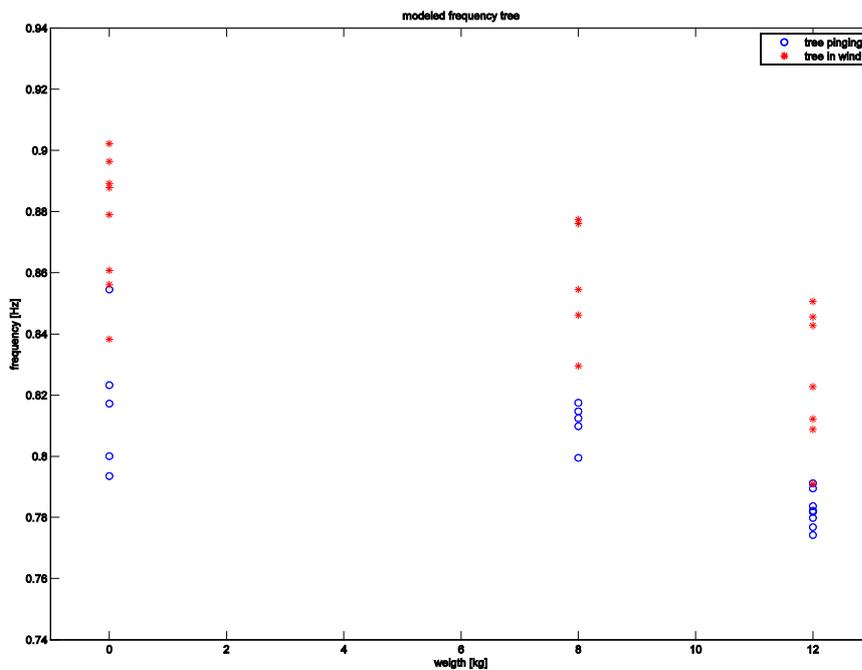


Figure 21: Modelled frequency of a tree with the wind experiment compared to the free sway test. The spread in data for a constant weight is 0.075 Hz. This spread is too large to detect changes in frequency due to variations in weight.

The tree with changing weight is compared with a tree with no added weight, Figure 22. This comparison is made to rule out the influence of changing conditions like the temperature or the wind during the experiments. There is no correlation detected.

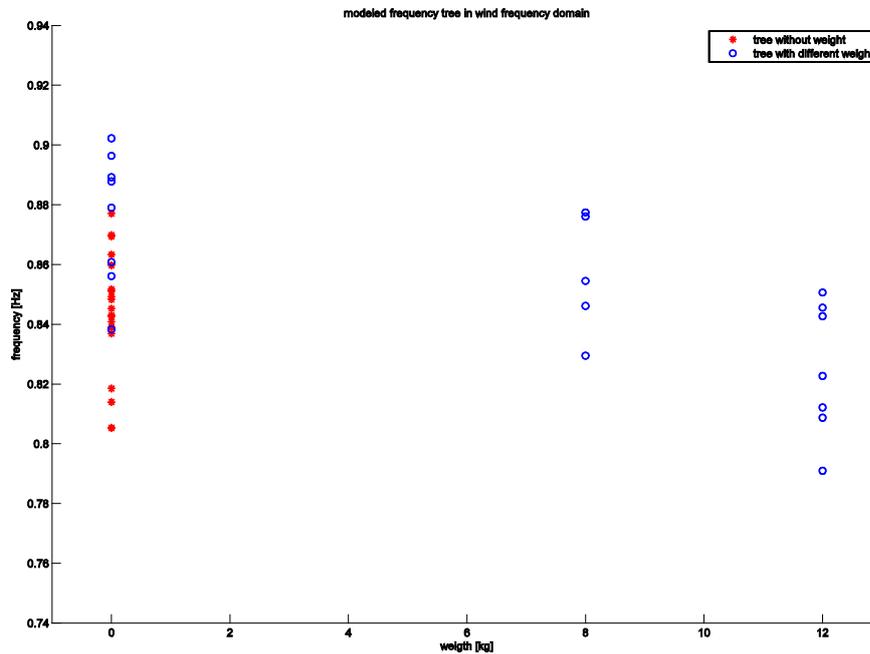


Figure 22: Modelled frequency of a tree for the wind experiment one tree with changing weight and one tree with a constant weight. The changes in frequency measured are not due to changes in wind.

Based on these results it is hard to say if a real change in frequency is observed with a changing weight. The average frequencies found during the wind experiments for 0, 8 and 12 kg are 0.88, 0.85 and 0.82 Hz.

The estimated weight of the tree is 30 kg, an increase of 12 kg in weight is an increase of 40%. This is much more than the expected 20% of water content variations. The expected change in frequency according to the theory is around half the change in weight in the opposite direction, see equation (9). With this increase in weight the frequency is supposed to decrease with 15.5% or 0.136 Hz. The modelled frequency decreases less than half, 6.8% or 0.06 Hz (this is based on the mean values).

4.4 Different time intervals for wind experiment

The influence of the selected time interval for the analysis of the wind measurements on a tree is presented in Figure 23. These are measurements from a tree with no added weight each box plot is formed with 23 points measured during 6 hours. Intervals of 1,2,5,15 and 30 minutes have been selected. These time intervals were used as input data for the Fourier transformation. Only for the 30 minutes range 11 points were modelled. The 1 and 2 minutes range have some outliers. The spread in data is smaller when longer time intervals are used for the analyses. Especially the minimum and the maximum value are closer to the median. The improvement is small though.

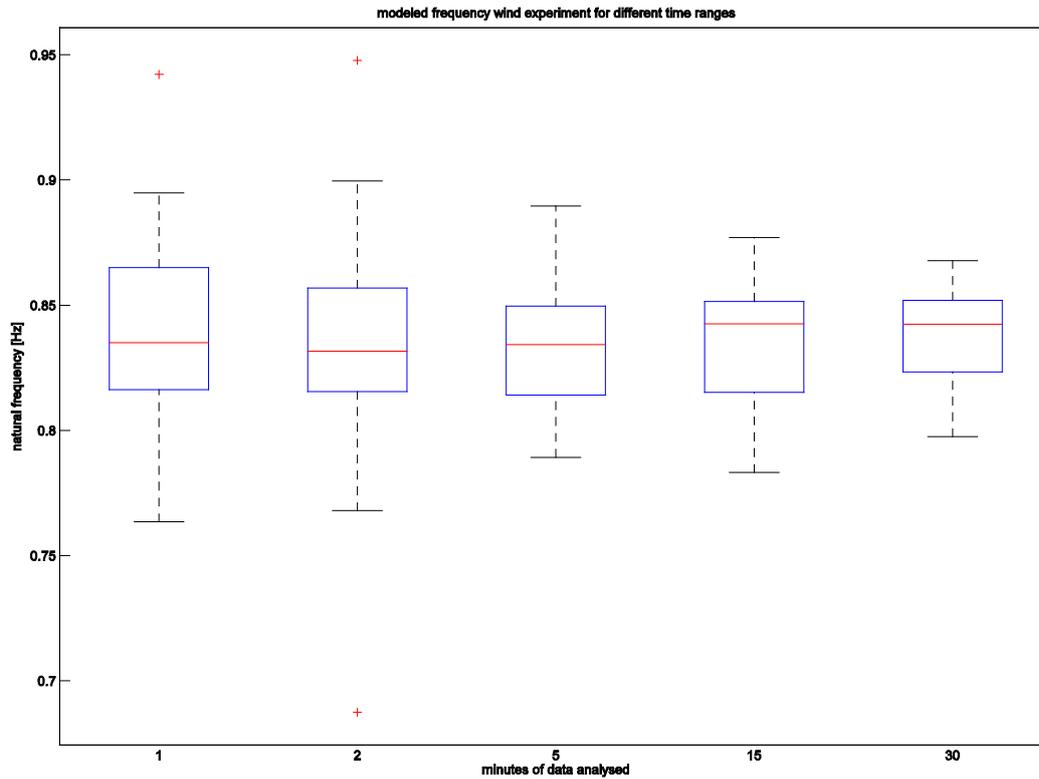


Figure 23: Boxplot for different time intervals of analysed data in the wind. The spread in data becomes smaller when longer time intervals are analysed. The improvement is small.

The same analysis is done for a tree with added weight, the total time of the measurement was the same but the weight added to the tree is changed 3 times. This means less points per weight were modelled. The results are presented in Figure 24. The spread in data decreases when longer time ranges are analysed. The spread in data does not change with different weights added to the tree.

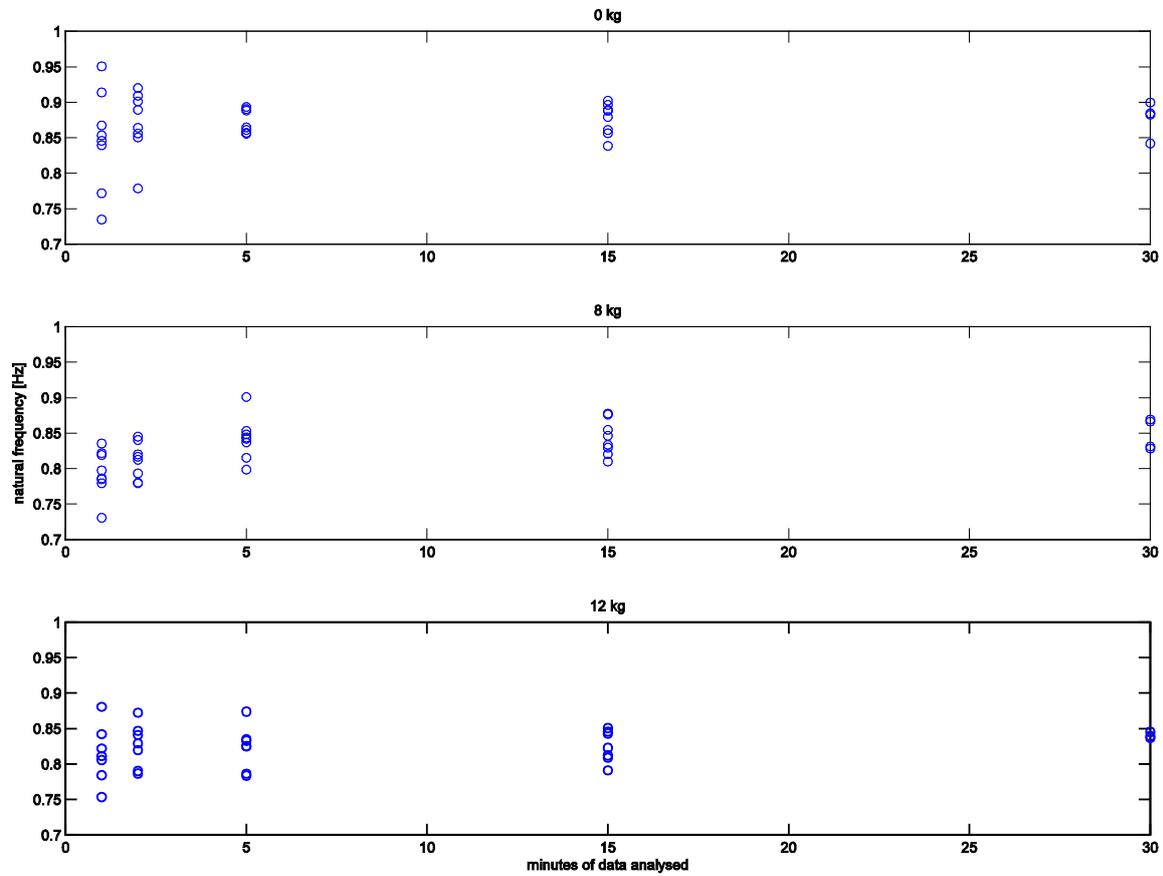


Figure 24: Modelled natural frequency compared with the time intervals used for the analysis, for 0, 8 and 12 kg. The spread of data is smaller when a longer time interval is analysed. The spread in data does not change when more weight is added to the tree.

The main movement direction of the tree varies a lot during the measurements in the wind, this is shown at the start of this chapter. When a longer time interval is used the variation in movement direction during one experiment will increase. This means the percentage of the variance captured by first principal component will be less. The mean percentages of the variance captured by the first principal component for the time intervals of 1, 2, 5, 15 and 30 minutes are 69, 68, 67, 66 and 65%. The percentages are decreasing but only with 1% for each interval. The 'main' movement direction for the different time intervals is presented in Figure 25. The longer the interval used for the analysis, the smaller the variation in direction of the first principal component. When the time interval chosen is long enough the tree has time to shake in every direction during one experiment. In the end the tree will move more in one direction, so apparently the tree has a preference to move in a certain direction, referred to as its 'favourable' movement direction.

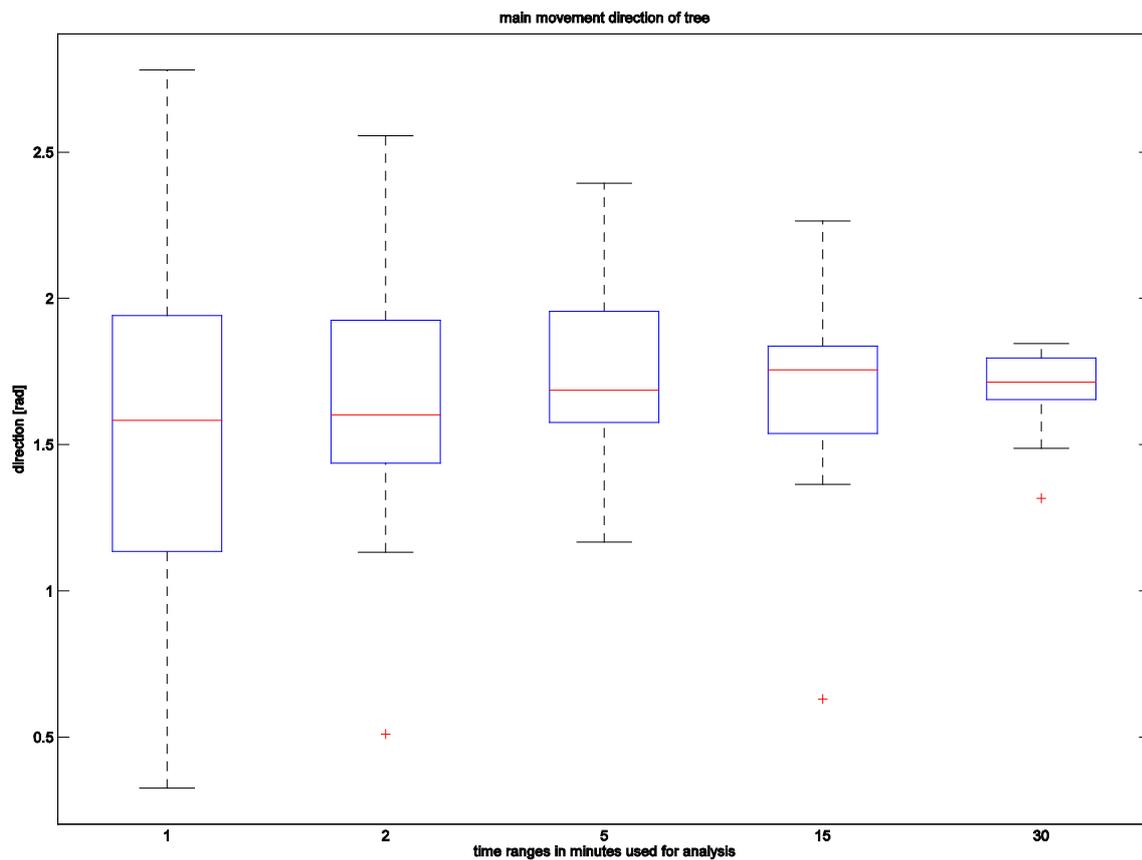


Figure 25: Main movement direction of a tree for different time intervals. The difference in movement direction decreases when longer time intervals are used for the analyses of the data.

5 | Conclusions

The main conclusion of this research is that the developed method is not accurate enough to detect frequency changes caused by variations of water content in trees. The accuracy necessary to measure water content fluctuations in trees, is the accuracy of the measurements performed on the simplified system. This is based on the theoretical expected frequency change for a first order spring-mass system. It is hard to reach this accuracy for measurements on trees because a first order spring-mass system is better represented by the simplified system than by the complex system of a tree.

Below a further elaboration is presented, at first the accuracy of the developed method is discussed. This is followed by an explanation of the implications of the movement direction of a tree. Subsequently the influence of the experimental setup and the differences between the simplified model and the tree are discussed. Finally the influence of the chosen model is explained.

5.1 Accuracy

The developed measurement method is not accurate enough to measure fluctuations in frequency caused by changes of water content in a tree. It is possible to measure natural frequency for both the simplified system and a tree. This is even the case if no manual pulse input is used but only the force of the wind is used to let the tree vibrate. The spreading in natural frequencies measured for a tree with a constant weight is 0.075 Hz and for the simplified setup this range is 0.015Hz. To measure fluctuations in weight caused by change in water content, the variation in the natural frequency measured for a constant weight must be in the order of 1%. The variation of 0.075Hz corresponds to a 8% range of the frequency and the fluctuations for the simplified system correspond to a change in frequency of 1.5%. The method can be used to measure the frequency of a tree but the changes in frequency caused by changes in water content are too small to detect.

The measured change in frequency due to a change in weight is lower than the theoretical expected change. The method is not accurate enough to confirm this, with certainty. If the frequency really changes less than expected, a possible cause can be that a tree is not behaving as a damped first order spring-mass system, which is also indicated in previous studies. Factors which increase the complexity of a tree are, the interaction of the branches, anisotropic mechanical properties and changing stiffness with fluctuations in temperature and water content. Frequency changes are influenced all these factors water content or in this research weight might be not the most influencing parameter.

5.2 Movement direction

The anisotropic mechanical properties of a tree are an important factor of the variation in the frequency values measured. The direction of the first principal component is used to analyse the data. In this way the data is analysed in the direction with most movement. For the sway experiments this is good choice because the sway direction was more or less the same during all the experiments. During a single experiment the tree mainly moved in one direction. This is visible in the amount of variance captured by the first principal component which is 97%. For the wind experiments the choice to analyse the data in the direction of the first principal component is disputable especially when thinking of the anisotropic characteristics of trees. The first principal component has a different direction for every measurements done on one tree. During a single wind experiment the tree will move in all the directions. On average only 60% of the variance is captured by the first principal component. To reduce the influence of the anisotropic mechanical properties the data can be analysed in one direction, though this will mean the variance captured will be lower.

The direction of the pull to initiate the vibration of the tree is the same during all the experiments. The movement direction of the first principal component was still varying over an angle of 0.3 radians. Additionally it is observed that during one vibration the tree changed in movement direction. This causes a decrease in model performance over the duration of a single vibration. There are two possible reasons for the changes in vibration direction during a single experiment. If the vibration is not initiated in the 'favourable' movement direction of a tree, the vibration direction will change during a single vibration. Changes in swaying direction can also be caused by other influences such as wind.

The time interval analysed per wind experiment also influences the direction of the first principal component. The variation in movement direction between different experiments, on a single tree, decreases with an increase in analysed interval length, per experiment. During large time intervals the tree will vibrate in every direction, but still the tree will mainly vibrate in its 'favourable' direction during this interval. This is not always the case because the wind can force the tree to move in a different direction. For smaller time intervals a tree will move more in one direction during a single experiment. Consequently the first principal component takes account for a higher percentage of the total variance, but the difference in movement directions of different experiments on one tree will increase. During this research a 30 minute interval was chosen as the maximum interval length. We suggest to analyse the correlation between the movement direction measured with longer interval lengths and the analysis of a core sample of the tree. These factors, both can help to indicate the 'favourable' movement direction of a tree. Analyses of the data in the 'favourable' movement direction can improve the accuracy of the developed method. The length of the analysed interval per experiment determines the amount of data points possible to measure during a certain time interval.

When weight was added to the tree the movement direction of the tree slightly changed. This is caused because the point weights were not exactly added in the gravitational centre. This means the observed change in frequency caused by weight might also be caused by a small change in movement direction.

5.3 Experiment setup and chosen model

The modelled frequencies for the sway experiments are consequently lower than the modelled frequencies for the wind experiments, for both the tree and the simplified system. The biggest difference between the two methods is the input force, likely this is the reason for this difference.

For the wind experiments it has been shown that the accuracy of the experiments dropped in periods with less wind. A certain amount of wind is necessary to perform these experiments.

This research showed that a stick with a weight on top can be properly modelled as a first order spring-mass system that relates the mass and the frequency. The uncertainty is introduced when this method is applied to model a tree. Three influences on the difference between the simplified system and the tree are mentioned. The movement direction is an important influence in this difference, the stick can only swing in one direction and the tree will move in every direction. Secondly the difference in amount of weight added compared to the own weight of the system is large. For the simplified system the maximum increase in weight was 700%, for the tree the maximum increase in weight used was 20%. As mentioned earlier in this chapter the frequencies measured for the simplified system were spread over a range of 0.015Hz for a constant weight. Most likely this range will not change when smaller amounts of weight are added. Thirdly a tree is a more complex system than the simple representation of a spring-mass system. Research has shown that even the assumption that the tree stands in the ground at a fixed point is not correct because the root system has influence on the movement of a tree. A more obvious influence on the vibration are the branches of a tree. This is also neglected when modelling a tree as a first order spring-mass system.

6 | Recommendations

Three advises are given which are useful when further investigating the method. These advises relate to the possible accuracy, the driving force and the amount of weight used for testing the method.

Results indicate that it is difficult to determine diurnal changes in weight of trees by measuring the natural frequency of a tree. There are two reasons why this is difficult; The theoretical change in natural frequency caused by changes in weight is small. Secondly trees are complex systems, the different branches, the anisotropic mechanical properties, the temperature, the stiffness and the water content all influence the natural frequency.

To overcome these difficulties and improve the accuracy of the method the following suggestions are made:

- Analyse the movement of the tree in one direction, to minimize the influence of difference in mechanical properties.
- Use symmetrical trees for the measurements, to minimize the influence of difference in mechanical properties for different directions.
- Analyse the difference in mechanical properties of a tree for different directions, to know which direction should be used to determine weight fluctuations.
- Use a divided weight instead of a point weight when increasing the weight, to simulate a more realistic weight distribution.
- Use a more realistic mathematical representation of a tree.
- Measure temperature, water content and wind spectrum during the experiments, because these parameters will have influence on the frequencies.

If the suggestions can improve the method such that it is possible to measure diurnal weight changes, it has to be proven that the diurnal weight changes are mainly caused by changes in water content in the tree. When the method is operational the influence of the following factors can be investigated to refine the method:

- Time interval used for analyses.
- The placement of the accelerometer

The above mentioned points are further elaborated in the following paragraphs.

Advise about Method

Results indicate that it is possible to measure weight changes of the simplified system by measuring the natural frequency. The weight increase was very large in comparison with the expected weight change due to water content. I suggest to investigate what the smallest weight fluctuations are that can be detected on the simplified system. This can give an indication of the highest possible accuracy for this method. The smallest weight change, which is expected to be detectable, is a variation in weight of 1,5%. This variation corresponds to the measured fluctuation in frequency determined with a constant weight.

It is advisable to focus on the method where the wind is used as a driving force. The measurements can be conducted continuously; the method is much easier to perform and the expected possible improvement in accuracy is higher than the possible improvement for the sway experiment. The accuracy can be improved because the wind experiments where analysed in different directions and consequently suffer from the anisotropic characteristics of trees.

Measurements should first be performed on small trees. Small trees will vibrate when a low amount of force is applied and a relative increase in weight is easier to achieve.

Suggestions for improving accuracy

To minimize the anisotropic mechanical properties of a tree symmetric trees should be chosen for testing this method. But a tree will never be fully symmetrical. Before starting with the experiments the mechanical differences of the tree for different direction can be analysed. The shape of the crown can give a good indication of the 'favourable' movement direction of a tree. With an increment borer the structure of the stem can be analysed. We suggest to analyse the measurements in only one direction instead of the direction of the first principal component. For the sway experiment we suggest to initiate the vibration in the 'favourable' direction to reduce the changes in movement direction during one vibration.

To simulate a change in water content, weight was added to the tree. This weight was added as a point mass at the start of the crown. The weight might have influenced the movement direction of the tree, because it is not possible to precisely attach the weight in the gravitational centre of the tree. A more divided weight in the crown is advisable, to simulate more natural conditions. A good way of this divided weight would be to measure a tree with and without leaves.

A possible cause of the decrease in accuracy of the method is that a tree is not behaving as a damped first order spring-mass system, which is also found in previous studies. Factors which increase the complexity of a tree are, the interaction of the branches and the anisotropic mechanical properties. To incorporate these factors a more complex model structure has to be used. Several different model structures are already proposed in literature, a finite element model can be used.

With an increase in weight the natural frequency was decreasing less than expected according to the theoretical relation between weight and natural frequency. The weight might not be the most influencing parameter for frequency changes. To get more inside on the influence of the wind, temperature and moisture content on changes in mechanical properties of trees, these parameters have to be compared systematically during the experiments.

Refine the method

When a longer time interval is used for analysis the variation in direction of the first principal component is smaller. This can indicate that a tree has a 'favourable' movement direction. It also can indicate that the average wind direction during longer time intervals is more constant than over shorter time intervals. To investigate this, longer time intervals should be measured and wind measurements have to be done during the measurements. It is observed that the accuracy of the wind measurements will decrease when there is little wind. Probably the accuracy of the method is also decreasing with too much wind. Because the mechanical properties of the tree will not have much influence when the wind is too dominant. There will be an optimum for the amount of wind.

The placement of the accelerometer can be optimized. The height of the accelerometer might not influence the results but it might be possible that for an optimal height the method can work with a lower amount of wind.

7

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Appendix

APPENDIX A	ACCELEROMETER	A
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APPENDIX C	SWAY METHOD.....	E
APPENDIX D	FIGURES	G

Appendix A | Accelerometer

Gulf Coast Data Concepts

www.gcdataconcepts.com

**USB Accelerometer
Model X6-1A**

1 Features

- 3-axis accelerometer
- User selectable ± 2 or $\pm 6g$ range
- User selectable sample rate of 10, 20, 40, 80, and 160 Hertz
- 12-bit and 16-bit resolution
- User selectable deadband and trigger
- Accurate time stamped data using Real Time Clock (RTC) with power back-up
- Convenient on/off button
- Data recorded to a removable microSD card (1GB included)
- Easily readable comma separated text data files
- Data transfer compatible with Windows or Linux via Universal Serial Bus (USB) interface (no special software)
- System appears as USB Mass Storage Device to Windows and Linux OS's.
- Standard replaceable "AA" type battery
- LED indicator lights for system status
- Weighs 2oz (55g) with alkaline battery

2 Applications

The X6-1A is applicable to:

- Continuous time stamped shock and motion monitoring of critical freight.
- Monitoring human motor activity, or actigraphy, such as exercise intensity or sleeping disorders.
- Automotive performance monitoring
- Educational purposes

3 Description

The USB Accelerometer X6-1A uses a low noise digital accelerometer sensor, precise time stamped data logging, microSD memory storage, real-time data access and USB connectivity. Acceleration is collected in X, Y, and Z axes and stored at a user selectable rate of up to 160hz. When connected via the USB to a personal computer, the X6-1A appears as a standard mass storage device containing the comma delimited data files and user setup files. The commercial standard "AA" battery provides extended life operation suitable to long term data acquisition applications.

Appendix B | Instantaneous frequency

The Hilbert transform is an analytical representation of an experimental signal (measured signal). This can be used to analyse the instantaneous frequency of a signal. The instantaneous frequency is used to analyse signals with a changing frequency over time. A measured signal $x(t)$ can be written as an analytical signal $z(t)$ according to equation (13), (Todoran and Tarnovan, 2009). Where $H(x(t))$ is the Hilbert transform of the measured signal, which can be obtained by the convolution of $x(t)$ with $1/\pi t$, equation (14).

$$z(t) = x(t) + iH(x(t)) \quad (13)$$

$$H(x(t)) = x(t) * \frac{1}{\pi t} \quad (14)$$

The instantaneous phase, ϕ , of $z(t)$ can be determined with the argument, equation (15). The angular instantaneous frequency, $\omega(t)$, is the derivative of this angle. When dividing by 2π the instantaneous frequency is derived, equation (16).

$$\phi = \arg(x + iH(x(t))) = \arctan(H(x(t))/x) \quad (15)$$

$$\omega(t) = \frac{d\phi(t)}{dt} = \phi'(t) \quad (16)$$

$$f(t) = \frac{\phi'(t)}{2\pi}$$

The instantaneous phase is a sawtooth, this reflects the varying of the local phase angle over a single cycle. The instantaneous phase of a part of the measured signal is presented in Figure 26.

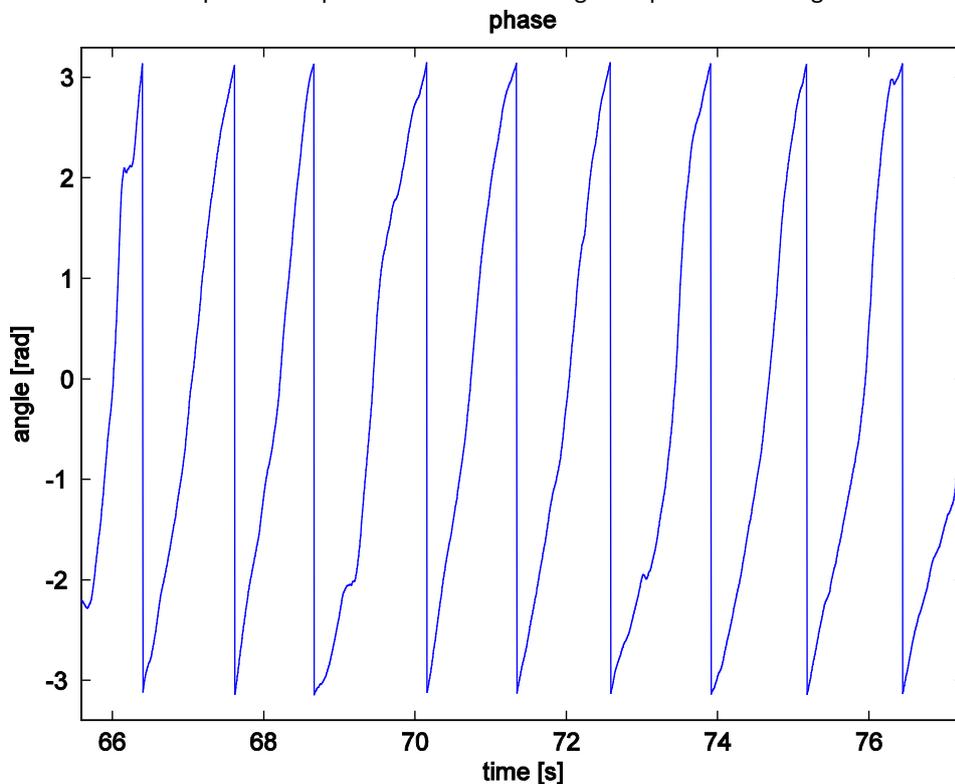


Figure 26: The instantaneous phase, the derivative of this sawtooth is the instantaneous frequency.

The instantaneous frequency of a measured signal is presented in Figure 27 (the blue line). The mean value of the instantaneous frequency during the presented time interval is 0.85 Hz. The total instantaneous frequency is also calculated with a straight line ($y=ax+b$) which is calibrated on the instantaneous frequency, this gave an instantaneous frequency of 0.92Hz.

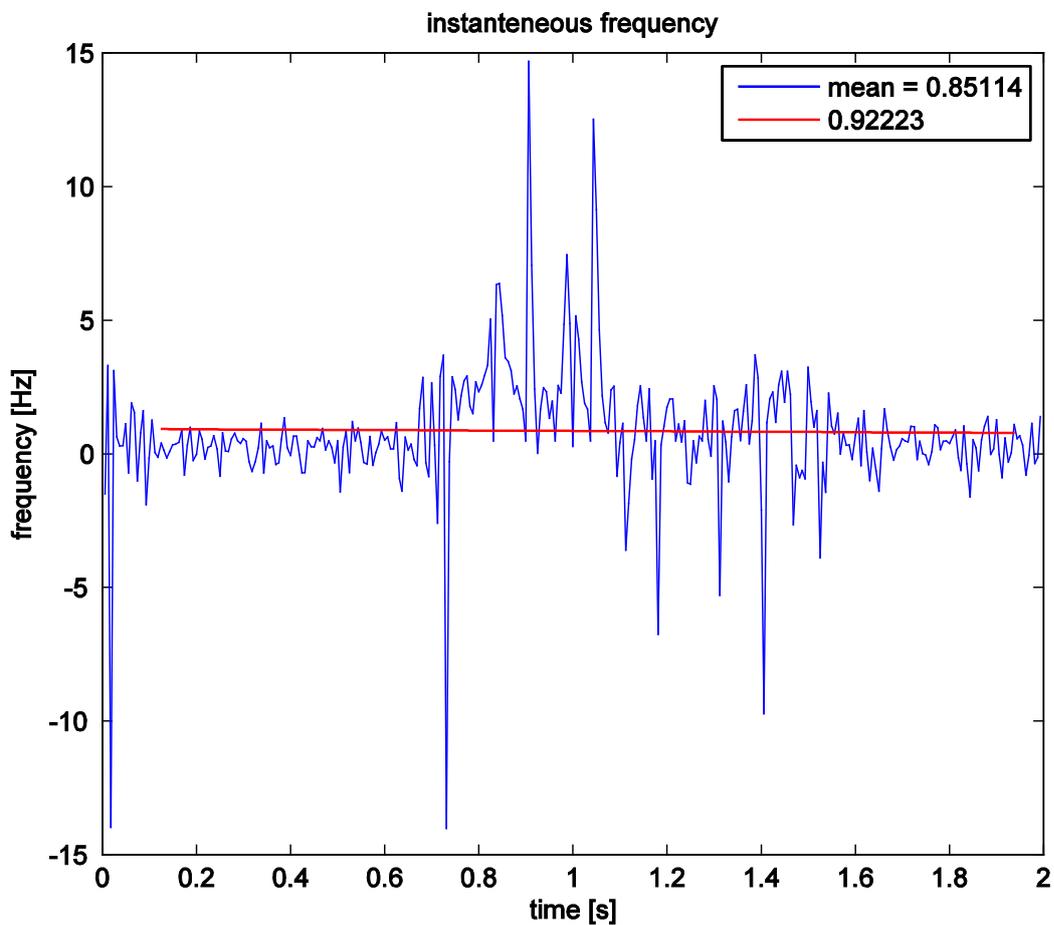


Figure 27: Instantaneous frequency in blue, in red a straight line calibrated on the instantaneous frequency.

Appendix C | Sway method

The tree is pulled out of its equilibrium with a tie down strap. A picture of the tie down strap used during this research is presented in. A rope was attached to the tree as counter force another rope was attached to a tree close by. The tie down strap was attached to one of the ropes.



Figure 28: Tie down strap.

The two ropes were attached with a release mechanism. The release mechanism was very easy the pen (presented in Figure 29) was fixed between the two ropes. The ring at the top of the pen is used to pull the pen away. A lot of force is necessary because of the friction with the ropes.



Figure 29: Release mechanism.

The total setup is presented in Figure 30. When the pen is pulled out the tree will start shaking.



Figure 30: Setup sway experiment.

Appendix D | Figures

The movement direction of the first principal component is presented in Figure 31. Data of two trees are presented one tree where no weight is added and one tree with three different weights added (0, 4 and 12kg). The direction of the tree with only one weight is most constant. The movement direction of the data measured for the 4kg is more constant as well. This might be caused by the wind which was more constant during this time interval.

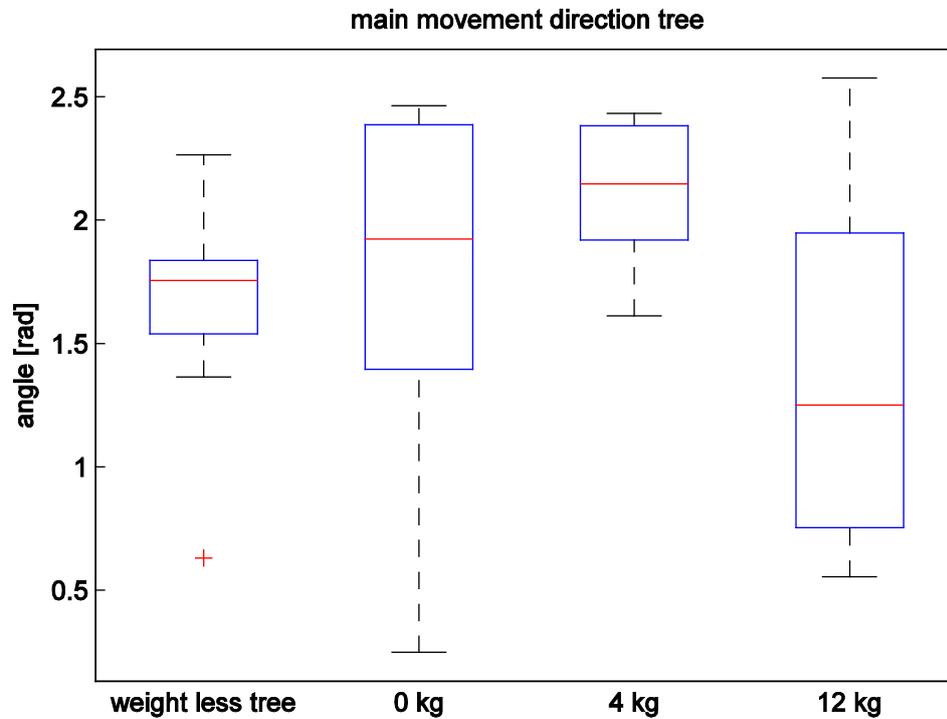


Figure 31: Movement direction of two trees. One tree without weight and one tree with where tree different weights where measured.

The angles of the same data are presented in Figure 32

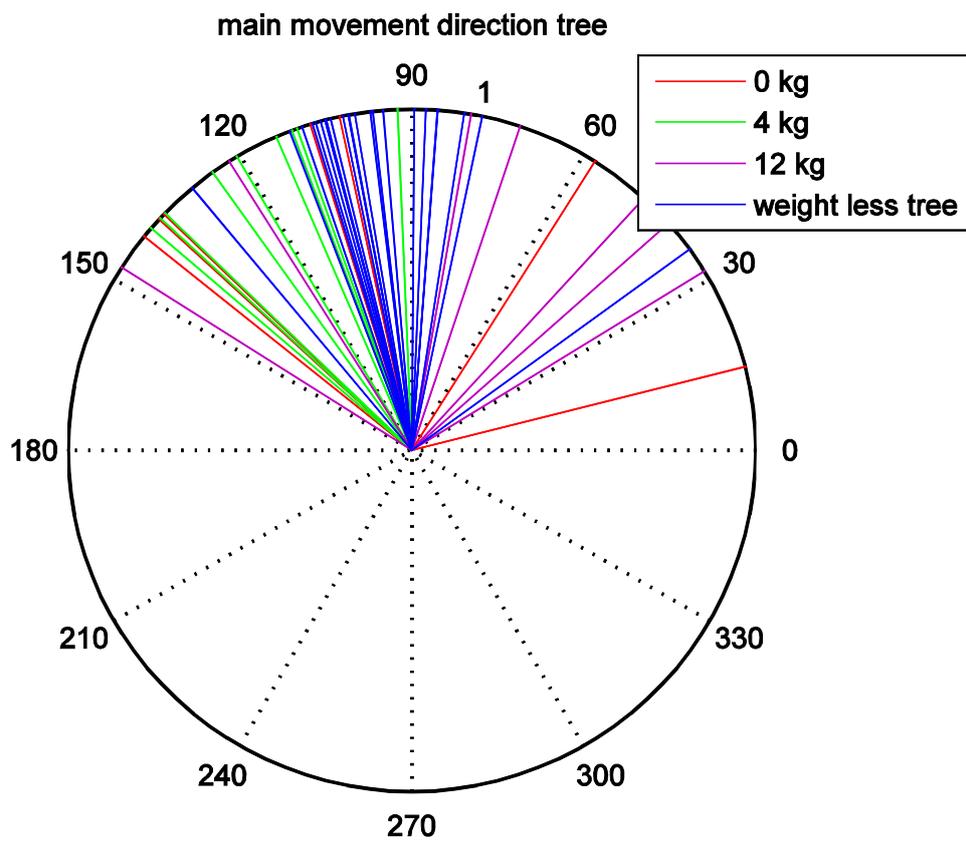


Figure 32: Movement directions of two trees one with and one without added weight.

A part of the raw measurement data is presented in Figure 33. Just before three o'clock the wind is dropping. This was analysed in the accuracy of the modelled frequencies as well.

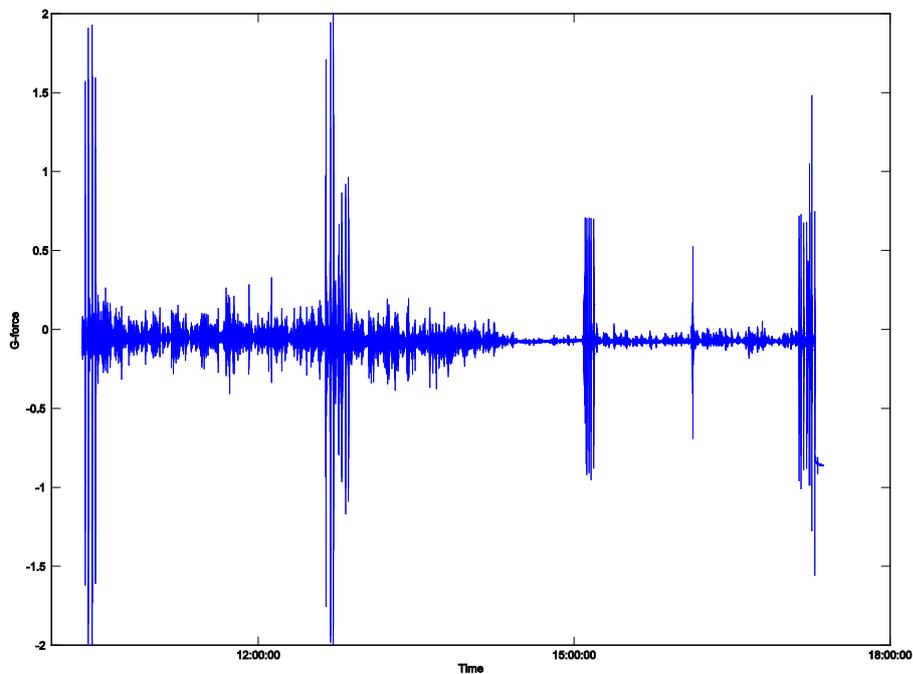


Figure 33: Raw measured data, just before 15:00 the wind is dropping so the stick is not vibrating anymore.