




Review

# A Review of Dynamic Tree Behaviors: Measurement Methods on Tree Sway, Tree Tilt, and Root–Plate Movement

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**Abstract:** Urban forest ecosystems are being developed to provide various environmental services (e.g., the preservation of urban trees) to urban inhabitants. However, some trees are deteriorated asymptotically without exhibiting an early sign of tree displacement, which results in a higher vulnerability under dynamic wind loads, especially during typhoon seasons, in the subtropical and tropical regions. As such, it is important to understand the tilt and sway behaviors of trees to cope up with the probability of tree failure and to improve the efficacy of tree management. Tree behaviors under wind loads have been broadly reviewed in the past literature, yet thorough discussions on the measurement methods for tree displacement and its analysis of broadleaf specimens are lacking. To understand the behavioral pattern of both broadleaf and conifer species, this paper presents a detailed review of sway behavior analysis from the perspectives of the aerial parts of the individual tree, including tree stem, canopy, and trunk, alongside a highlighted focus on the root–plate movement amid the soil–root system. The analytical approaches associated with the time–space domain and the time–frequency domain are being introduced. In addition to the review of dynamic tree behaviors, an integrated tree monitoring framework based on geographic information systems (GIS) to detect and visualize the extent of tree displacement using smart sensing technology (SST) is introduced. The monitoring system aims to establish an early warning indicator system for monitoring the displacement angles of trees over the territory of Hong Kong’s urban landscape. This pilot study highlights the importance of the monitoring system at an operational scale to be applicable in the urban areas showcasing the practical use of the Internet of Things (IoT) with an in-depth understanding of the wind-load effect toward the urban trees in the tropical and subtropical cities.

**Keywords:** urban trees; tree tilt; tree motion sensor; tree–wind interaction; smart sensing technology



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## 1. Introduction

Urban forests are essential components to the makeup of urban ecosystems to maintain environmental quality and sustainability. Urban green resources consist of standalone trees, parks, gardens, designed green areas, urban and peri-urban woodlands, and large green conservation areas. Trees reduce atmospheric carbon dioxide concentrations [1], minimize the occurrence of urban hazards (e.g., flooding, drought, and landslides) [2], ensure water security [3], and sustain and enhance biodiversity [4], in which the ecosystem can be balanced and regulated [5]. In urban and peri-urban areas, trees provide the aesthetic value [6] of the inhabited streetscape.

Often planted under stressful conditions, urban trees are threatened by multiple factors, e.g., natural disturbances (earthquake, strong wind, typhoon), invasive species,

construction damages [7], and negligent management practices [8]. Natural disturbances, e.g., windstorms, hurricanes, and tropical cyclones may lead to the snap of branches or the crown parts of urban trees, and even resulting in uprooting events. A thorough understanding of wind-tree interactions is of paramount importance to minimize economic losses and damages to human life caused by tree failure.

Tree movement is interwoven with wind flow, which highly depends on the degree of loading intensity acting on trees. If the wind loading exceeds the maximum root–plate tension limit, some weakened and unhealthy trees may tilt along with the wind direction increasing the risk of tree failure, which would cause injuries or even death. Tree tilt measurement is an important yet challenging research topic for arborists, researchers, and urban forestry managers. Previous studies integrated on the relationship between trees and wind speed have been preliminarily explored by providing tree–wind patterns and wind speed indices [9,10]. With the multi-purpose of sensors and different measurement methods, tree displacement angles can be obtained accurately and efficiently. Tree tilt information can be associated to the stability of trees. Meanwhile, the displacement of tree roots and stem helps demonstrate the extent of soil slope movement [11] and also to estimate the likelihood of flood hazard [12].

The objective of this paper is to provide a comprehensive review of the technologies for the measurement of tree sway, tree tilt, and root–plate movement under wind load, with a special focus on broadleaf trees. A detailed summary of geographic coverage, study period, and field investigation approaches of related literature is presented. This review will elaborate and explain the tree tilt behavior caused by multiple internal and external factors in the sophisticated tree–wind mechanical system, and four quantitative measures of vertical displacement for broadleaf specimens are summarized. Finally, an integrated framework of the tree tilt monitoring system of Hong Kong’s urban tree is introduced. This would also cast insight onto better management of urban trees and forests, proposing an application of the early warning system before the occurrence of tree failure events.

## 2. The Methodology of the Literature Review

This paper reviews a wide range of sources, including journal papers, conference proceedings, books, and online resources between the year 1962 and 2019 through the keywords search in different combinations, i.e., tree sway, tree uprooting, root anchorage, natural frequency, static and dynamic pulling, wind tunnel test, tree architecture and tree–wind interaction relating to tree sway, tree tilt, and root–plate movement. A collective of motion sensors are being explored, such as the accelerometer, inclinometer, and gyroscope, where the comparison to understand tree tilt measurement with or without wind effect is elucidated. Lastly, a case study of the tree monitoring system will be introduced to speculate the practicability of the tilt monitoring application, with a test-bed experiment to establish the tree monitoring system being undertaken in Hong Kong.

## 3. Review of Methods and Techniques

This section provides a detailed review of studies on the measurement of tree behaviors under wind loading, with a focus on the aerial parts of selected trees. First, an overview of the study sites that briefly describe the geographic coverage, physical attributes of sample trees, and selection of the study period are introduced. After that, the behavior of trees subjected to wind loading was investigated through a series of in-situ experiments and simulation modeling. During the in-situ measurement and simulation modeling, various sensors and equipment have been designed to measure the displacement of trees and wind behavior. In the end, the analytical approaches associated with the time-space domain and the time-frequency domain are introduced to filter out significant factors that could model the mechanism of wind-tree interactions.

### 3.1. An Overview of the Study Sites

#### 3.1.1. Geographic Coverage

Related studies on tree–wind interactions have been carried out in many places over the world, such as Asia (Hong Kong [13], Macau [14], and Mainland China [15]), the United States [16–18], Canada [19–21], the United Kingdom [22,23], Europe (Portugal [24], Czech Republic [25], and Germany [26]), and Australia [27]. Meanwhile, the field measurements were conducted on many tree species, and the sample tree species can be categorized into deciduous broadleaf trees (Lime trees (*Tilia × europaea*) [28], Oak trees (*Quercus*) [16,25,29,30], Maple trees (*Acer* spp.) [26], Hickory trees (*Carya* spp.) [31] and Pear trees (*Pyrus* spp.) [32]) and conifers trees (Pine (*Pinus* spp.) [18,30,33], Spruce (*Picea* spp.) [20,34,35], Douglas fir (*Pseudotsuga menziesii*) [36] and Ironwood (*Casuarina equisetifolia*) [37]). The measurement approaches of tree displacement of these two botanical categories are different from the others.

#### 3.1.2. Tree Species and the Physical Attributes

To study the sway or tilt behavior of trees and understand the interactions between trees and wind, the selection of tree specimens is considered as the foremost consideration. Based on the structure of leaves, tree species can be divided into two botanical groups—conifer and broadleaf trees. Compared with broadleaf trees, coniferous trees have been further studied in the recent two decades. In the category of coniferous trees, three major species have been well-explored, which are pine [38–40], Douglas fir [41], and Spruce [42–44]. On the other hand, the broadleaf species undertaken in this study include Maple tree [26], Oak tree [32], Birch (*Betula* spp.) [31], Black locust tree (*Robinia pseudoacacia*) [45], Pear tree [32], Poplar tree (*Populus* spp.) [28], Walnut tree (*Juglans* spp.) [45], etc. One field study [46] mainly focuses on the deciduous forest in Wythan Woods, Oxford, where Sycamore (*Acer pseudoplatanus*), European ash (*Fraxinus excelsior*), and English oak (*Quercus robur*) are the dominant species. The selection of tree species can be at a single tree level, or a mixed stand setting with both conifer and broadleaf trees. In most cases, certain species of particular tree were selected to be studied [47].

Sample trees are selected for field surveys or simulated modeling based on multiple criteria. For in-situ measurements, the selection criteria are categorized as follows:

- Location: usually described as (i) urban areas or peri-urban areas and (ii) the latitude, longitude, and exposition of test sites;
- Number of tree species: single species [48] or multiple species [49];
- Health status: healthy or with different kinds of defects [28] on stems or roots (wound, diseased, crossed, hollow, etc.).

Meanwhile, physical details of trees specimen are elaborated, e.g., the inherent tree features (tree species [48], tree slenderness, tree mass, tree crown size [32], canopy direction, diameter at breast height (DBH) [36], tree elasticity, and damping ratio [50]). The surrounding environment, e.g., the wind speed [51], soil type [42], test type [27,52], and meteorological conditions [49] are usually introduced as the environmental background of tree behavior analysis.

Under various circumstances of field investigations, the selection criteria of trees are different. In the case of high wind events or static pulling tests, sample-trees can be selected based on the criteria mentioned above. In wind tunnel experiments, selection criteria are more stringent due to the detailed design of tree models. Sample data used to build models can be restricted to symmetrical, open-grown, 3–5 m tall saplings [52]. Sitka spruce (*Picea sitchensis*) trees, based on age, tree size, and the strip of trees [23], were selected in a wind tunnel experiment, based on which tree models were designed.

Due to the complex structures of the tree stand, various aerial parts of trees have been studied independently, e.g., tree trunk, stem, branch, and canopy. While the studies on conifer trees have long been focused on tree canopy, the canopy is defined as a reference case of tree scales. For broadleaf trees, the studies mainly focused on tree stem and tree trunk [53]. In Freiburg, Germany [26], the response of a Norway maple (*Acer platanoides*) under wind loading was investigated within nine months. The measurement is a case-by-

case basis, in which different aerial tree parts including tree stem, tree branch, and tree trunk and different techniques (e.g., time-series analysis, Fourier analysis, and wavelet analysis) will be adopted to analyze wind data and tree response by advanced assessment.

### 3.1.3. Selection of Study Period

Phenology is a significant factor for tree sway behavior analysis, as deciduous broadleaf trees usually shed leaves in autumn. In different seasons, natural wind loading varies at various levels. From the reviews of related studies, high-speed wind events in different seasons have been studied individually, e.g., tropical cyclones that mainly occur in summer, wind loading in winter conditions [26,49], and wind storms that may occur all over the year [54].

The impacts of several hurricanes on the urban forest in the US were studied when several hurricanes occurred in 2004 and 2005 [55,56]. With a special concern on hurricanes in the southeastern US, tree species are the dominant factor to the high survival rate in wind, and a statistical comparison demonstrated that tree species with higher wood density had a greater chance to survive under strong wind. Lee and Jim measured the sway behavior of one broadleaf deciduous flame tree during a tropical cyclone in terms of sway magnitude, sway amplitude, and in-situ wind properties in Hong Kong [57]. A combination of triaxial accelerometer and sonic anemometer and the comparison of inter-branch sway behavior denoted that the mean sway magnitude ( $SM_{MEAN}$ ) is an important parameter to analyze tree–wind interactions in summer, especially during typhoon seasons.

On the other hand, in another study, severe cold conditions were studied as a special case [49]. Different from tropical storms, the low temperature in freezing conditions could also be an indicator of tree displacement. This study was conducted in Howland, US, which measured the tree sway frequencies of 18 conifer trees continuously using biaxial clinometers from August 2009 to January 2010, in addition to the wind speed, wind direction, and temperature measured with sonic anemometers. This in-situ study showed that freezing weather has posed some consistent effects on tree sway frequencies. For frozen trees loaded with snow, the degree of loads was an important indicator for reduced tree sway frequency quantification. The effect of snow loading on tree sway frequency was studied [58] where the results show that the presence of snow (1–2 cm of snow present in the crowns) will lead to a 30% of reduction in the natural frequency of two Sitka spruce trees, which have compromised to other study speculating the additional mass of snow [59] would lead to a significant reduction in natural frequency. In another study, the frequency of lime trees in both summer and winter was measured [28]. The results denoted that the sway frequency of lime trees had smaller values in summer.

## 3.2. Investigation Approaches

According to studies on tree–wind interactions, the behavior of trees subjected to wind loading was investigated through a series of in-situ experiments and simulation modeling. In real-world circumstances, experiments are carried out under dynamic loads (high wind events) or static loads (static pulling tests) to investigate the threshold of the standing trees. On some occasions, wind tunnel test for a wider scale of simulation is an effective and frequent-used approach to investigate the tilt of trees under simulated wind loading.

### 3.2.1. High Wind Events

The measurement from natural wind loading is the most direct way to understand the working principle of tree–wind interactions. Experimenting with high wind events is a widely used approach to investigate responses of trees under wind loading, which is quick and easy to set up. As stated in Section 3.1.3, high wind events occur mainly in summer, and most of the studies focused on tropical cyclone cases [55–57] affecting the tree movement. In autumn and winter, the responses of several deciduous tree species under windstorms were also investigated [24], showcasing that more than 60% of trees and branches fall in Lisbon during cold seasons. The period of measurement is usually undertaken during the high wind events, where the events can last for 3 days to 10 days [56] or 9 months [26]. The advantage of

investigations under high wind events is that the practical tree responses to wind loading are genuinely exhibited when compared to static pulling and wind tunnel tests.

### 3.2.2. Static Pulling

The static pulling test was discussed in some studies [52] as an auxiliary tool to mimic natural wind loading. By artificially pulling a tree with the aid of equipment, the test aims to determine the critical wind force and corresponding wind speed to the tip-point of breaking the trees. In one study [60], a Sitka spruce was made to sway by repeatedly pulling and releasing on a rope. In another study [61], the static pulling test was carried out among 10 *Eucalyptus* trees in Australia, and the overturning moment ( $M$ ) and the tilt angles ( $\varphi$ ) of the structural root zone of trees were recorded. With the tree height varying from 17.2 m to 27.0 m, the maximum structural root zone was tilted at  $0.60^\circ$  with an overturning moment of 47.7 kNm (max applied moment  $M$ ). In Switzerland [42], the static pulling test was conducted to measure the response of 66 Norway spruce (*Picea abies*) trees under wind loading. The results denoted that the resistive turning moment  $M$  at the stem exhibited strong nonlinear behavior to the pulling force, resulting in the anchorage strength reached to a lower value for larger trees.

The advantage of static pulling is that a repeated in-situ measurement could be carried out at any time without the need for unprecedented natural windstorms. At the same time, static pulling is usually compared with dynamic wind conditions to demonstrate valuable results. From the comparative study conducted in [61], different root rotational angles were measured under static and dynamic wind loading with the same sample of tree groups. However, static pulling tests have some limitations. One characteristic shows that smaller branches and twigs bend in high wind events which have not accounted for [27]. Yet, it is refuted that the pulling test, as a type of axiom of uniform stress, providing a simplification method to model the complex structure of the aerial parts of trees [22]. Given the ample evidence, although static tree pulling tests alone might not be convincing to explain the mechanism of tree–wind interactions, it is still useful to provide evidence and give support to the tree critical movement under the simple design of testing environment and models.

### 3.2.3. Wind Tunnel Tests

A simulation approach to analyze tree–wind interactions is wind tunnel experiments [23,34,62,63]. Unlike in-situ measurements under high wind events and the static pulling test, model trees were designed to simulate the real-world conditions in a wind tunnel test. Therefore, tree models are simulated to respond with arbitrary velocity and turbulence [34], while tree sample quantity in the model can vary at different scales, e.g., 12,000. Flexible model trees were used for the wind tunnel simulation at a scale of 1:75. The wind tunnel test on model trees proved that the overturning moments of trees were insensitive to the wind direction.

Due to the artificial design of tree models, wind tunnel tests can reduce some complex factors that occur with in-situ measurements, such as the presence of snow at the canopy top and the physical status of different tree species. Therefore, the influence of wind on canopy structure can be investigated more directly in wind tunnel tests. The limitations of wind tunnel tests laid on that the model trees are only a simplified simulated forest. Therefore, the simulations are only the estimates of reality. Conclusions obtained from wind tunnel experiments are mainly used as a reference. Meanwhile, the quantitative results derived from the tests are less convincing compared to results from natural wind loading observations.

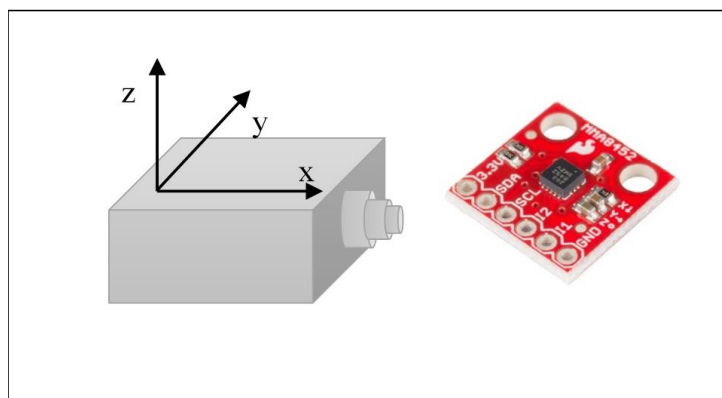
Due to the unpredictable nature of high wind events, static pulling tests and wind tunnel experiments are generally considered as a supplement and seldomly applied for in-situ tests. Nevertheless, these two modeling approaches still provide useful information for analyzing the modeling results of measurements.

### 3.3. Instruments for Tree Behavior Measurement

The measurement of tree tilt is heavily dependent on the specifications and the design of equipment. During the in-situ measurement and simulation modeling, various sensors and equipment have been designed to measure the displacement of trees and wind behavior. For non-destructive technologies to investigate the mechanism of tree–wind interactions, the components of tilt measurement sensors, i.e., triaxial accelerometer [57,61] and clinometers [31,33,49], are introduced. Other instruments are also used for tilt measurement, including laser Doppler interferometers [28] and sonic anemometers [40].

#### 3.3.1. Tilt Measurement

**Accelerometers:** An accelerometer (see Figure 1) is an electromechanical device for acceleration measurement and can measure acceleration on one, two, or three axes. In tree–wind studies [61,64], accelerometers are often used as tilt sensors that are attached to the base of a tree stem or lower tree trunk and branches sometimes. The sampling frequency is usually 20 Hz. James et al. [26] used a triaxial accelerometer to measure longitudinal motion (X-axis), lateral motion (Y-axis), and vertical motion (Z-axis), to assess the branch sway of a flame tree in Hong Kong [57]. This tree motion sensor (TMS) has an angular sensitivity at  $0.01^\circ$ , a sampling frequency of 20 Hz, and a response time of 400 ms.

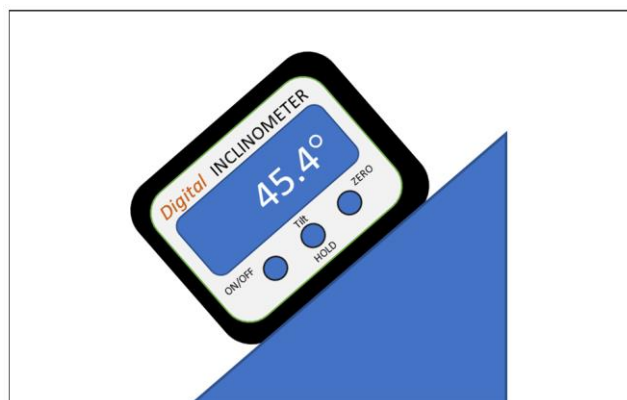


**Figure 1.** A triaxial accelerometer measures the vibration in three perpendicular planes (X, Y, and Z) simultaneously.

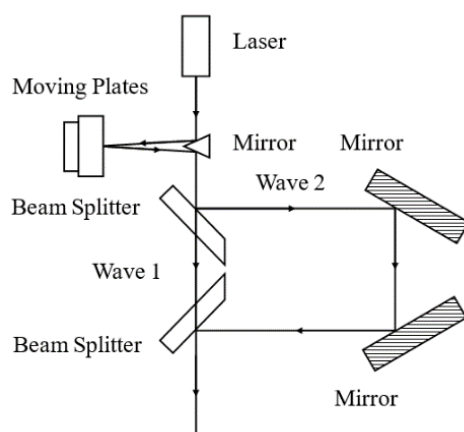
**Clinometers:** Clinometers (Figure 2) are instruments used for measuring angles of tilt to gravity's direction. Biaxial clinometers can be mounted on the corresponding sample trees to measure the angular position of tree stems with a sampling frequency of 10 Hz [31,33]. A study carried out in the United States [49] suggested that biaxial clinometers were ideal for tree sway measurement due to the fast response time and simple installation. Three biaxial clinometers (model 902-45, Applied Geomechanics, San Francisco, CA, USA) are applied to measure wind-induced tree displacement [39] of Scots pines (*Pinus sylvestris*) as well.

#### 3.3.2. Sway Measurement

**Laser Doppler Interferometer:** Laser Doppler interferometer (Figure 3) is a laser-based instrument. Commonly used to measure the natural frequencies of buildings, this device can measure the vibration amplitude and frequency difference between the reference beam and test beam. By making the non-contact vibrant measurement of trees, this device measures the power spectrum of tree velocity and obtain frequencies of trees. There was example for lime trees [28], the natural frequencies were measured using a laser Doppler interferometer.



**Figure 2.** A clinometer is used to measure the angular position of the aerial parts of the sample tree (e.g., tree stem, tree branch, and tree trunk).



**Figure 3.** Basic components of a laser Doppler interferometer. The laser beam is directed at the surface of interest, based on which the vibration amplitude and frequency can be extracted due to the motion of the target surface.

When compared to the accelerometer, the main advantage of the laser Doppler interferometer is that this device can make non-contact vibration measurements of targeted trees, while sometimes the beams may be difficult to get the target accurately located. The natural frequency of trees can serve as a reference when compared to the sway frequency of trees measured under natural wind loading, thus examining tree stability.

### 3.3.3. Wind Speed Measurement

**Anemometers:** Anemometers are specially designed for the measurement of wind speed and wind direction. The Leda triaxial anemometers were used to measure within-canopy turbulence [65] of four plastic trees in a wind tunnel test. Schindler et al. used sonic anemometers to measure near-surface airflow properties and their spatial variability at the measurement site [40]. The advantages of anemometers is attributed to the sensitivity of the device, and commercially affordable. However, the battery charging of anemometers can give a pause during wind data collection, causing the data mismatch as a result.

### 3.4. Analytical Approaches

After the raw data acquisition from various equipment and devices, tree response data and wind data are processed with different techniques to filter out which factors could model the mechanism of wind-tree interactions. The multidimensional nature of tree responses to wind loading denoted that a single analytical approach might not be convincing to analyze the tree sway and tilt behavior. Therefore, multimodal analysis is a common method to investigate the mechanism of tree–wind interactions.

### 3.4.1. Conventional Statistical Analysis

- Fundamental Statistics

Statistical analysis is an essential tool for tree displacement measurement. Basic statistics such as mean, standard deviation, minimum and maximum can provide information for the preliminary understanding of acquired raw data. To study the dynamic properties of Pear and Oak trees, means of trunk height, diameter, crown height, crown width, and trunk mass provide a pertinent data description of two broadleaf species in the study [32]. Based on the statistics, analysis of variance (ANOVA) is applied to determine whether the natural frequency of trees and damping ratio differed with the cycle, pruning, or other environmental factors.

- ANOVA Test

Analysis of variance (ANOVA) is a series of statistical models to analyze group means in a sample. Ronald Fisher first introduced the term analysis of variance and developed ANOVA [66]. In tree-related studies, ANOVA is an efficient statistical tool to generalize the t-test to more than two groups. It is computationally efficient and robust by providing strong statistical analysis.

A two-way ANOVA was used to test atmospheric stability and temperature condition [49] to seek a variable that can significantly predict tree sway. To study the mechanical parameters that may be a component of the tree failure model, ANOVA was utilized to investigate the effect of species and wind on several factors, e.g., drag, bending moment, stress, the factor of safety, and drag coefficient [67]. For each broadleaf species (Freeman maple (*Acer freemanii*), Swamp white oak (*Quercus bicolor*), and Shingle oak (*Quercus imbricaria*), experimental results showed that massive trees experienced a greater drag and drag-induced bending moment. According to the research on Bradford pear (*Pyrus calleryana*) and Chestnut oak trees (*Quercus prinus*) [67], tree mass can reliably predict the bending moment of the aforementioned three tree species as tested in Virginia, United States.

- Regression Analysis

Regression analysis is a statistical method to discover the relationship between dependent and independent variables. Regression analysis was used in [22] to identify the positive relationship between average wind velocity and movement of the smaller branches. Bunce et al. [31] used stepwise multiple regression to determine the factor that may influence the fundamental vibration frequency of 39 trees in southern New England. The study found that slenderness, defined as  $DBH \times H^{-2}$ , is a dominant factor affecting the natural frequency of trees, regardless of tree species.

### 3.4.2. Time-Frequency-Based Techniques

Time domain data can be converted into frequency-domain data using the following equation:

$$f = \frac{1}{T} \quad (1)$$

where frequency ( $f$ ) is the reciprocal of the time ( $T$ ). In the frequency domain, wavelet analysis [68] and Fourier analysis [69] are two main techniques to measure tree tilt and branch motion in the time-frequency domain.

- Wavelet Analysis

Wavelets are useful in processing nonstationary signals [70]. In the field of tree tilt measurement, wavelet analysis can expand time-series into time-frequency space, thus analyzing the intermittent nature of coherent structures. As a mathematical tool, the wavelet transform can be used to analyze rapid changing and transient signals. In one study [38], interactions of wind load and tree response of Scots pines were first analyzed by decomposing a time-series using a family of wavelet functions. In Freiburg, Germany, wavelet analysis [33] was applied to measure the wind stem displacement of three Scots pine trees under wind loads.



- **Fourier Transform**

Fourier Transform decomposes a function of time (a signal) into frequencies. Comparing to wavelet analysis, Fourier transform expands the function in terms of trigonometric polynomials. Conventional Fourier transform techniques are sensitive to small tree movements, based on which a reliable spectrum can be obtained [28].

Fourier transform was applied to the fluctuations of stem displacement of Scots pines [33] in y-direction and x-direction. Four peaks were found, followed by a Biorthogonal decomposition (BOD) [71]. The BOD can be used to decompose an m-degree signal into m modes in the time-space domain. Fast Fourier analysis [31] was used to generate a power spectra of frequencies. To examine the freezing effect of on tree sway frequencies, a spectral density Fourier analysis was performed to find the fundamental frequency peak of conifer trees [49]. The low-frequency peaks were considered to characterize the natural frequency of the tree stem.

### 3.4.3. A Combination of Multiple Analysis

Apart from using wavelet analysis and Fourier transform independently, there is a trend to combine these two techniques to analyze the impact of wind load on trees. In a study [33], wavelet analysis and Fast Fourier Transform (FFT) were used together to investigate tree responses to wind loading. Fourier Transform was used to determine the frequency range of Scots pine trees, and wavelet analysis was used to analyze coherent structures in a turbulent flow. Lee and Jim [57] used wavelet analysis (the time-frequency-based technique) and F-test (the time-space-based technique) together to monitor the sway behavior of a broadleaf flame tree.

## 4. Discussion

### 4.1. Impacting Factors of Tree's Sway and Tilt Analysis

The ambient environment poses a great influence on trees. When exposed to natural hazards, aerial parts of trees may bend and break. Trees become less stable when exposed to strong wind events such as windstorms, hurricanes, and tropical cyclones frequently. External forces such as rockfall, debris flow, and avalanches [35] could also affect the stability of trees. The capacity of a tree to withstand under wind loading varies with physical status, inherent tree features, and different botanical groups, in addition to the external forces on trees.

Thus, an in-depth investigation of tree responses to wind can help better understand wind-induced damage to trees, and prevent the occurrence of potential root hazards. To investigate tree responses under wind loading, considerations on tree attributes and physical attributes are first introduced, followed by the summary of internal and external factors of tree movement.

#### 4.1.1. The Specialty of Inherent Tree Features—Internal Factors

- **Wood Elasticity**

Young's modulus of elasticity (E) [72] is a numerical constant named after the British physicist Thomas Young. It describes the resistance of a solid structure in only one direction when under lengthwise tension or compression. Young's modulus can be described mathematically using the following equation:

$$E = \frac{\text{stress}}{\text{strain}} \quad (2)$$

where *stress* is the force that could cause deformation and *strain* is the ratio of the change.

Wood has independent mechanical properties in three perpendicular axes—longitudinal (L), radial (R), and tangential (T) [73]. Accordingly, the three moduli of elasticity are denoted by  $E_L$ ,  $E_R$  and  $E_T$ , respectively. The modulus of elasticity, which is determined from bending, is usually species-specific [31], and used to measure the bending moment and the natural

frequency of trees. For an open-grown sugar maple (*Acer saccharum*), the elasticity of trees was considered with three other parameters (i.e., tree slenderness, DBH, and the damping ratio) as major factors that could affect tree sway [48]. For eight different deciduous broadleaf tree species [31], tree elasticity is speculated to be negatively correlated with fundamental vibrational frequency (FVF) significantly, but not the leaf-off-above-freezing condition.

- Natural Swaying Frequency of Trees

Some of the previous studies [28,51,60] focused on the measurement of the natural swaying frequency of some tree species, e.g., Lime tree, Sitka spruce, and Scots pine. The periodic motion of trees can be described by amplitude, frequency, and time. Frequency ( $f$ ) is the reciprocal of period ( $t$ ), the amplitude is defined as the maximum displacement. At nature swaying frequency, trees oscillate under free vibration with occasionally very high amplitude. The swaying of trees increases with heightening wind speed and can be used as an important indicator of tree stability under windy conditions.

An early study measured the natural swaying frequency of Red pine (*Pinus resinosa*) and White pine (*Pinus strobus*) trees by using a stopwatch [74]. The bole and mass of the crown of diameter/height (D/H) ratios were considered as two main factors leading to the sway period of trees. In Baker's study, natural swaying frequencies of the lime trees were measured using a laser Doppler interferometer [28]. Baker found that tree geometry and seasonality could produce notable changes in natural swaying frequency with the findings, which had recorded higher magnitude in winter and lower in summer from the measurement at Nottingham University, UK. The major cause leading to the significant difference in natural tree frequency could be attributed to the fully in-leaf condition of trees in summer with dry ground, and leafless condition in winter with the rather moist ground. According to one review study [36], the natural swaying frequency of conifer trees can be reliably estimated from tree height (H) and diameter at breast height (DBH).

Compared to studies on conifer trees, the study of the natural frequency of broadleaf trees is limited. Free vibrations of Bradford pear and Chestnut oak were measured [32] using pull-and-release tests in Massachusetts and Virginia, USA. For both species, they found that the pulling direction would not affect the natural swaying frequency, yet the sway frequency could increase through the pruning exercises and reduce the likelihood of tree failure. The findings of this dynamic property can help to refine models to predict tree failure with the continuous measurements of tree tilt.

Frequency is a significant index of tree stability regarding the natural vibrational nature of trees. By measuring the resonant frequency of 10 Sitka spruces [60] in the static pulling test, the maximum frequency is 0.37 Hz, and the minimum frequency is 0.26 Hz for each whole tree. For the stem of Sitka spruce, the maximum frequency is 0.70 Hz and the minimum frequency is 0.43 Hz. For broadleaf trees, the fundamental frequency of one Flame of the Forest [57] was measured, showing a range from 0.47 Hz to 0.59 Hz. According to one study [28], the natural frequency of lime trees was recorded higher in winter (0.62 Hz) and lower in summer (0.25 Hz). Nevertheless, the accuracy of the natural frequency measurement depending upon the sensing method and sensor configuration.

- Damping Ratio

The damping ratio describes the decay of oscillation after a disturbance, e.g., gusty winds, water waves, or earthquakes [50]. Damping is of great importance for trees to withstand heavy wind loading over time. During the windstorm, only the mechanism of passive damping can reduce the effect of the wind on the trunk and roots [50]. Generally, the damping ratio of trees can be divided into two types, i.e., internal and external [75]. Internal damping is caused by the internal friction of tree stems [76]. External damping is mainly due to the aerodynamic drag on the foliage and contact between the crowns of adjacent trees [36].

For open-grown deciduous trees, the natural frequency and the damping ratio of trees have been considered as two important parameters that may lead to tree failure [32]. For

conifer trees, experimental results of 24 Norway spruces show that velocity proportional damping (viscous damping) could be used to model tree–wind interactions [43].

- Diameter at Breast Height (DBH) and Height (H)

Diameter at breast height (DBH) is a standard measurement of expressing the diameter of the trunk of a standing tree. Despite different definitions of DBH in previous studies, the convention now is the diameter at 1.3 m above the ground level [77]. DBH is always considered as a direct parameter to represent tree sway and has been used in most tree–wind studies [31,65,78].

As a function of tree height (H) and DBH,  $DBH \times H^{-2}$  [31,36] is often used to calculate tree slenderness. At the same time,  $DBH \times H^{-1}$  is another definition of slenderness and that was used in some studies. Tree slenderness is a coefficient of trees [79], which is a significant indicator of sway frequency measurement.  $DBH \times H^{-2}$  is expected to be positively correlated with frequency [32] and is considered correlating with three other measures (tree slenderness, the elasticity of trees, the presence of foliage, and temperature) [31,78]. This expression is an important parameter to measure the tree sway frequency of all sites and species.

#### 4.1.2. Impact of External Forces on Trees

- Wind

The tree–wind interaction is dynamic and determined by the degree of wind loading and the natural frequency of trees. As a natural force, wind can affect the physical condition of trees, leading to the distortion of the tree root anchorage, the tilt of tree stems, or even falling. There are many approaches to calculate the wind load imposed on a tree, among which the most significant parameter is wind speed. To measure wind speed, the anemometer is the major instrument. In several studies [51,57], wind speed is a significant factor in tree tilt because the swaying of trees increases with the wind speed. The wind speed over a tree canopy can be defined using the following equation [80]:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right) \quad (3)$$

where  $z$  is the height above the surface,  $u_*$  is friction velocity,  $k$  is von Karman's constant (around 0.4),  $d$  is the zero-plane displacement, and  $z_0$  is the aerodynamic roughness.

By exploring the relationship between wind speed and stem displacement of four Scots pines in the southern Upper Rhine Valley, time-series decomposition was used. The results showed that wind-induced excitation caused minor effects on the overall tree movement on the sample trees [78]. Yet, according to one study on the Flame tree [57], the wind speed in terms of four corresponding measurements, which are the mean wind magnitude ( $WM_{MEAN}$ ), maximum wind magnitude ( $WM_{MAX}$ ), mean wind amplitude ( $WA_{MEAN}$ ) and maximum wind amplitude ( $WA_{MAX}$ ) tested on a single broadleaf Flame tree in Hong Kong, the results showed that mean sway amplitude ( $SA_{MEAN}$ ) was the preferred parameter that can reflect the association of branch sway and wind speed.

Although there are manifold effects of wind on trees, some common features can be utilized to estimate tree responses under wind loading, e.g., wind speed, wind direction, and decomposed wind vectors.

- The Root–Soil System

The mass of the root–soil plate and the shear strength of the soil are considered by Jonsson et al. [35], which indicates two soil-related components that may contribute to the rotational moment of trees. A root anchorage model for Sitka spruce was developed, regarding the tree and soil as a simple mechanical system [44]. The soil resistance [81] and the weight of the root–soil plate were considered contributing to the overturning forces of trees [35,82], while conversely the root–soil system of 66 mature Norway spruce trees was studied to investigate the turning moment ( $M$ ) at three different locations in Switzerland,

where the function of tree size and weight are more significant rather than that of the soil resistance [42].

Overall, the mechanism of tree tilt associated with tree displacement and tree decay are sophisticated systems and are affected by a combination of internal and external factors in which only one single parameter alone cannot explain the mechanism of tree tilt thoroughly. The combination of multiple indicators and measures could be more convincing to examine the tree status under windy conditions, measure the rotational angles of tree root tilt, and predict the stability of trees in high wind events.

#### 4.2. Four Major Measures for Tree Tilt and Sway Analysis

The rotational angle of the root is a direct measure of the tree tilt. Considering the in-situ studies, the angular sway data is usually obtained from the inclinometer. Although numerous studies have focused on tree sway behavior analysis [19,49,83], the exact vertical deflection of tree roots has not been clarified. The main concern, however, is that angular sway data of trees cannot efficiently reflect the tree architecture and help understand tree sway behavior. Therefore, different measurements have been used to analyze the vertical displacement of trees. Here, four commonly used measurements (Table 1) are summarized as (1) the angular sway data, (2) the vertical displacement, (3) the sway frequency of trees, and 4) the critical wind speed that would trigger a tree to sway, tilt, and even collapse.

**Table 1.** Existing measures for tree tilt analysis.

Measure	Unit	Instrument	Description
Angular Sway Data	Degree	Accelerometer	The tilt angle of a tree recorded as the response of wind loading (the sensor is often attached to the base of the tree)
Vertical Displacement	Meter	Inclinometer	Vertical deflection measured from the center of tree mass
Sway Frequency	Hz	Calculation	The fundamental frequency peak
Critical Wind Speed	Km/h	Anemometer	The wind speed that could cause the tree to snap at 1.3 m

The vertical displacement of a mixed stand (including coniferous trees and broadleaf trees) was calculated from angular tree sway data using the following equation [49]:

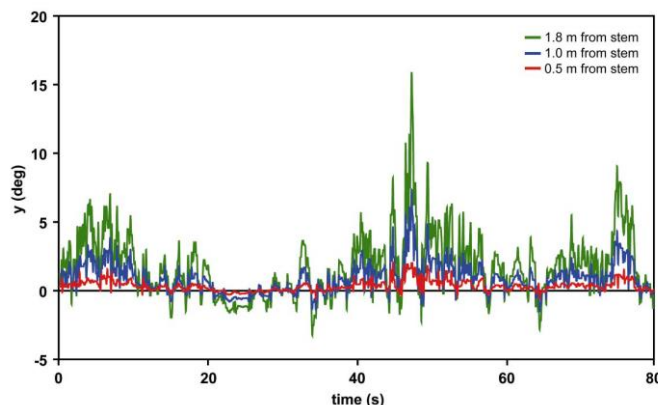
$$V = K \times \left( \frac{1}{3 * l_{ct}} + \frac{l_{ct}}{L^2} - \frac{l_{ct}^2}{3 * L^3} - \frac{1}{L} \right) \quad (4)$$

where the vertical deflection of the tree ( $V$ ) measured from the center of the mass is a function of the center of mass measured from the top of the tree ( $l_{ct}$ ), the height of the tree ( $L$ ), and the stiffness coefficient ( $K$ ). The vertical displacement was then converted to sway frequency data using the Fourier Transform, where the low-frequency peaks were characterized as the natural frequency of tree stems.

The tilt angle of *Eucalyptus* tree root zones was measured using a tri-axial accelerometer for the static pulling test. The results [61] demonstrated that the maximum structural root zone was tilted and the records during the static pulling tests were  $0.6^\circ$  among 10 *Eucalyptus* specimens, and  $0.88^\circ$  under wind loading conditions among 18 *Eucalyptus* trees (*Eucalyptus* spp.). The numerical values of tree tilt from this study significantly represented a reference to the sway behavior analysis of *Eucalyptus* and some broadleaf trees with similar kinds of features as *Eucalyptus*.

Figure 4 shows the angular sway data measured from a fully leafed Norway maple tree branch. The values of vertical branch displacement ( $\Phi$ ) increase against the installation height of biaxial inclinometers that was elevated from 0.5 m to 1.8 m. For the vertical displacement measured with a 0.5 m distance from the stem, the vibration range is within

5 degrees. The preliminary results of this sampled broadleaf tree denoted the swaying pattern of tree aerial parts is complicated and anisotropic, and the response characteristics of tree branches could be determined by the direction of the wind.



**Figure 4.** Vertical displacement  $y$  (deg) of a branch (no.15) of the Norway maple tree, measured throughout 80 s at 0.5 m, 1.0 m, and 1.8 m from the tree's stem [53]. The Maple tree shows the highest vertical displacement (around  $17^\circ$ ) when measured at 1.8 m from the stem.

The critical wind speed (CWS) of 397 trees in a broadleaf forest in the UK was estimated based on a linear function of tree height, DBH, species, and tree architecture [46]. The tree architecture, although complicated and species-specific, is measured by the cylinder models. Results obtained from this study showed that tree size and architecture are the main drivers to speculate CWS, and trees are at higher risk in summer if exposed to the same wind speed, despite the field data predicted lower CWS in summer than in winter, denoting that the presence of tree foliage is significantly affecting the imminent risk so the physical attributes are important for estimating CWS.

#### 4.3. A Closer Look at Broadleaf Trees

One characteristic of the deciduous broadleaf trees differentiated from conifer trees is that some specimens usually shed leaves in autumn and turn into the status of leafless in winter. For deciduous broadleaf trees, the presence of foliage and the temperature are two major factors [31] that may influence the sway frequency of tree trunk. A comparison between summer and winter denoted that Lime trees with the presence of foliage tend to have lower magnitudes of sway frequency in summer than that in winter [28].

When it comes to the change of tree branches, pruning may increase the natural frequency of conifer trees [83]. On the contrary to conifer trees, pruning broadleaf trees [32] can reduce the likelihood of wind-induced tree failure, as measured from the free vibrations of two open-grown broadleaf trees, i.e., Bradford pear and Chestnut oak.

Empirical research has demonstrated that the natural frequency ( $f$ ) of conifer trees is highly correlated to  $\text{DBH} \times H^{-2}$  [43,83]. Similar to the results obtained from conifer trees, the  $\text{DBH} \times H^{-2}$ , often defined as slenderness, is regarded as the dominant factor that may affect the sway frequency of tree trunk of several broadleaf species (e.g., Birch, Hickory, and Maple) [31]. Baker stated that a lime tree, also a broadleaf tree, tends to have a lower natural frequency with a higher DBH [28].

Overall, to investigate the tilt behavior of broadleaf trees under wind loads, parameters derived from conifer trees studies, e.g.,  $\text{DBH} \times H^{-2}$ , are pertinent for analysis. Meanwhile, seasonality is considered an important factor, as the fully leafed and leafless condition could have a huge impact on the stability of broadleaf trees.

#### 4.4. A Large-Scale Integrated Tree Monitoring System in Hong Kong

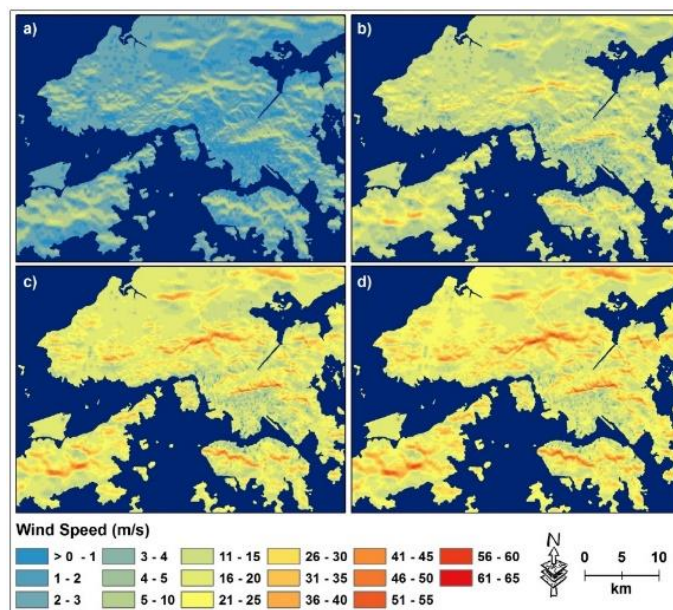
The overview of tree motion sensors and tree–wind interactions shows that the tree responses under wind loads have been widely investigated. In this point of view, the main

challenges of current studies are three-fold. First, many previous and ongoing studies focused on boreal forests, in which coniferous trees are the main research targets. The number of studies carried out in urban and peri-urban areas along with existence of a mix of broadleaf and conifer in the tropical forest is relatively limited and short of available means. Second, a tree monitoring system that can examine, modulate the stability of trees, and estimate potential root hazards have not been provided so far in related studies. Third, tree management over a wide variety of trees planted in the urban area of Hong Kong lacks near-instant monitoring cases in which the tree failure could pose hazards with immediate adverse effects in case of strong wind events. Thus, a large-scale tree monitoring system in Hong Kong is presented to examine the instant status of the tree's root motion and halt the associated hazards that might appear.

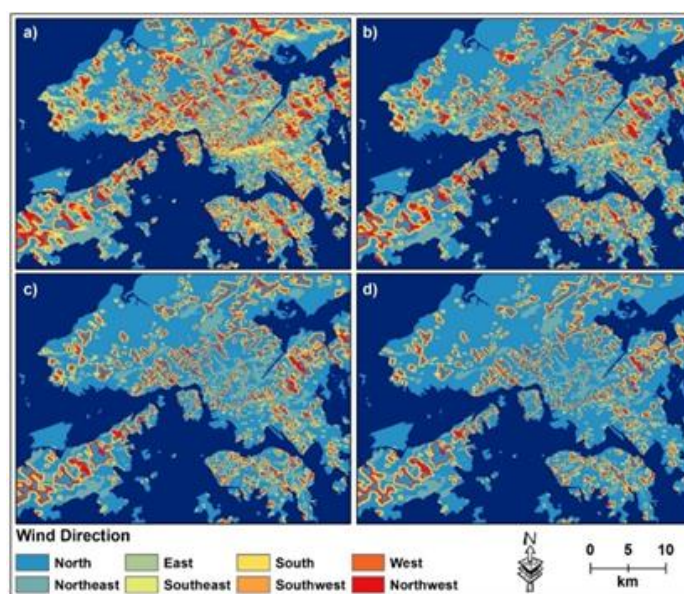
Hong Kong is situated in the sub-tropical zone, with a minimum temperature usually above 10 degrees Celsius in the urban area. The climate has cultivated a wide spectrum of tree species that are mostly discovered in a sub-tropical forest and some belong to temperate forest, yet in general, the broadleaf trees, whatsoever the evergreen and deciduous are deemed as more adaptable to grow in Hong Kong.

To study the wind-induced damages to broadleaf trees in Hong Kong, quantitative measures in other broadleaf trees studies can be regarded as reference stated in Section 5. Meanwhile, many tree research studies on the resistance and resilience during storms such as hurricanes [55,56], tropical cyclones [57], and windstorms [24,54] are of great importance to better understand the dynamics of tree–wind interactions.

Typhoon Mangkhut was an extremely powerful tropical cyclone affecting devastatingly to Hong Kong in 2018. On 16 September 2018, the Hong Kong Observatory issued Typhoon Signal No. 10, which is the highest level of tropical warning signals under the schematic framework of typhoon signal set out in Hong Kong. During the 10-h strong wind, we have simulated the wind speed (Figure 5) and wind direction (Figure 6) for the whole Hong Kong city using the Airflow Analyst. It is a 3D computed fluid dynamics (CFD) extension software [84] running under ArcGIS. Through the direct and convenient use of GIS data, Airflow Analyst can create simulations and visualize the wind flow on the platform.



**Figure 5.** Wind speed measured in Hong Kong (18 September 2018) using the Airflow Analyst at different ground heights: (a) 1 m, (b) 9 m, (c) 22 m and (d) 30 m.



**Figure 6.** Wind direction measured in Hong Kong (18 September 2018) using the Airflow Analyst at different ground heights: (a) 1 m, (b) 9 m, (c) 22 m and (d) 30 m.

This system is the first-ever to build up a massive scale monitoring system to oversee 8,000 trees using geographic information systems (GIS) in Hong Kong, through the data collected from the communicating sensors with the platform and database instantly. Two pilot sites with high traffic and pedestrian density were selected—Kowloon East and Wan Chai—and another 10 districts are identified for test-bed sites. A variety of tree species are investigated, including Chinese hackberry (*Celtis sinensis*), Ironwood (*Casuarina equisetifolia*), Hong Kong orchid tree (*Bauhinia* spp.), Kassod tree (*Senna siamea*), Lemon-scented gum (*Eucalyptus citriodora*), Candlenut (*Aleurites moluccana*), Sea hibiscus (*Hibiscus tiliaceus*), Flame tree (*Delonix regia*), and Indian coral tree (*Erythrina variegata*), and many of other broadleaf species in Hong Kong. Measuring the displacement angles of these tree species can provide valuable information about tree responses under wind loads, thereby monitoring the anomalies of the physical status of these trees simultaneously on a massive scale.

In line with the monitoring system, the smart sensing technology (SST) sensor is developed to measure the tree tilt in urban areas of Hong Kong with an in-built systematic notification mechanism to send the alert to the registered correspondences once the tree tilt angle over the threshold values. The SST sensor integrates high precision accelerometers, geomagnetic sensors, and high-performance microprocessors. The SST sensor supports low-power operation mode, and the operation lifetime can be up to three years, subject to the mode frequency to be adjusted in the practical operation.

To transmit and record data, a low-power wide-area network (LPWAN) technology is used in this integrated monitoring system. LPWAN [85] is designed to allow long-range communications at a lower bit rate. Comparing to the local area network (e.g., Bluetooth and Wi-Fi technology) and cellular network (see Table 2), LPWAN is more efficient in low power consumption and low cost positioning. Therefore, it can be used to transmit data via sensors that operate on a long-lasting battery.

**Table 2.** A comparison of different technologies on data transmission for tree monitoring.

	Local Area Network (LAN)	Lower Power Wide Area Network (LPWAN)	Cellular Network
Advantages	Well established standard	<ul style="list-style-type: none"> <li>Covers a larger area</li> <li>Low power</li> <li>Low cost</li> </ul>	High coverage
Disadvantages	Limited area coverage	Emerging standards	Cost of ownership
Examples	<ul style="list-style-type: none"> <li>Bluetooth</li> <li>Wi-Fi</li> </ul>	Long-range wide area network (LoRaWAN)	3G 4G

The time-space-based data collected from the SST sensors are converted to the time-frequency domain, and based on the threshold values of the tilt angle of root-plate that is determined by a collaborative consideration of several inherent tree features (e.g., DBH, wood elasticity, the damping ratio) and external forces acting on trees (e.g., wind speed and wind direction). Once the exceedance of the threshold values was recorded, the monitoring system will trigger a notification message from the SST sensor (Figure 7), while the relevant information will be shown on a GIS-based platform for big data management.

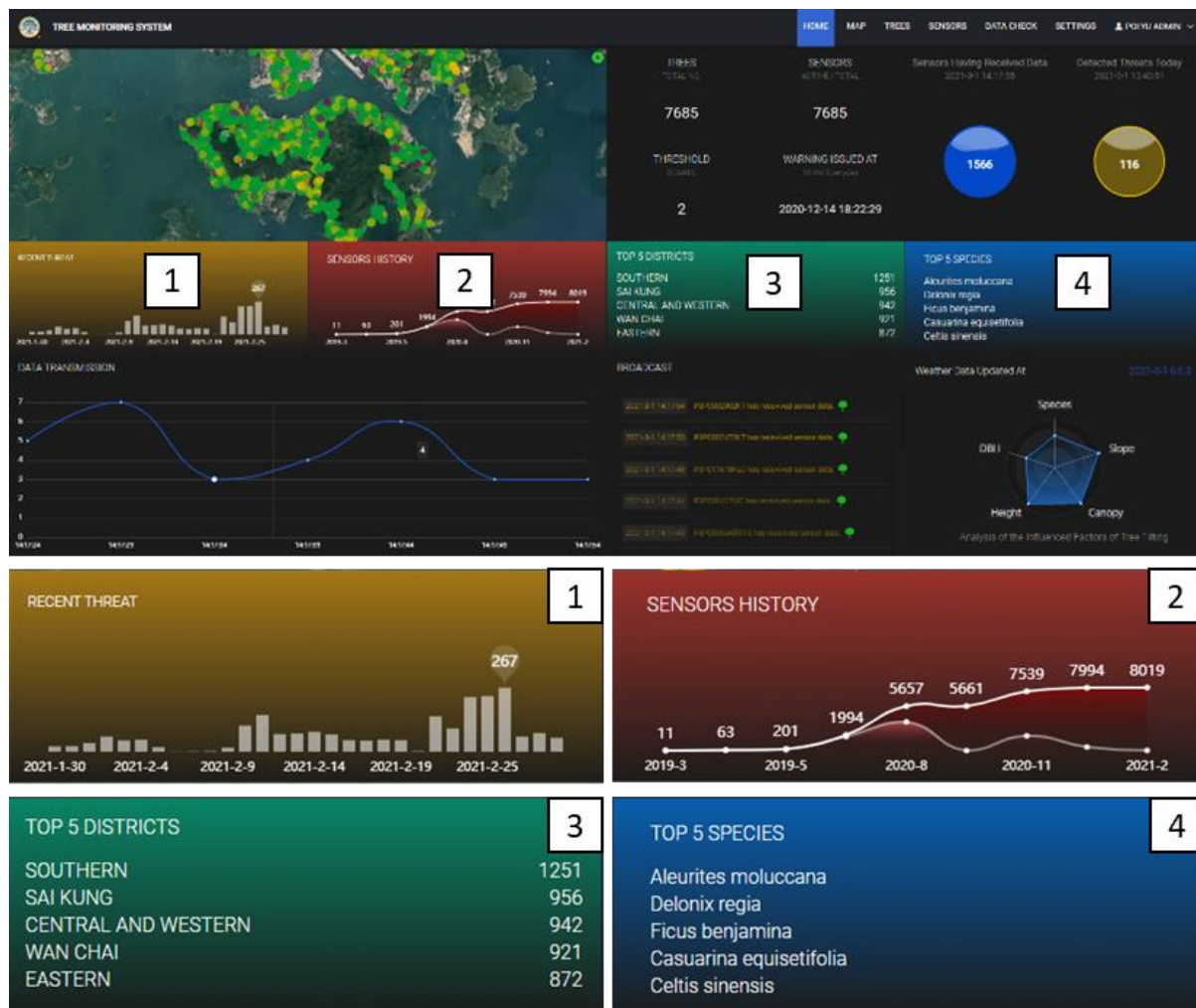


**Figure 7.** A prototype of a smart sensing technology (SST) sensor. It integrates high-precision accelerometers, geomagnetic sensors, and high-performance microprocessors to measure tree tilt in the urban areas of Hong Kong.

As a significant part of the tree monitoring system, a dashboard with an easy-to-use user interface is developed for an application, displaying information such as temperature and wind, the location of individual trees, the number of activated and total sensors, influential factors under tree tilt and swaying conditions. With the fully equipped and informative dashboard (Figure 8), the status of the respective tree tilt and the operation status of sensors can be viewed instantly. The sampling interval of each data is subject to change based on the weather and this will affect an up-to-date status being shown on the dashboard where the longest gap of duration of data taken is 12 h.

Big data create a paradigm shift to data-driven research [86] and have enabled multiple functionalities of the GIS. A GIS platform is designed to store, compute, manipulate, analyze, manage and present geographic data. As a valuable tool, the GIS-based platform can manage different types of spatial data and display data in the way of thematic maps. Conventional GIS platforms were limited to low spatial data storage, spatial analysis, and spatiotemporal visualization performance [87]. With the utilization of big data analytic techniques, large-scale data storage is optimized. Meanwhile, an integrated GIS-platform is provided for smart devices to process and analyze spatial-temporal data in real-time and display the results in all types of thematic maps.





**Figure 8.** The first generation of dashboard development to demonstrate sensor condition, tree locations and attributes, weather, and location information. (1) Number of threatened trees in Hong Kong at different time periods; (2) Number of sensors being installed in Hong Kong at different time periods; (3) Top 5 districts in Hong Kong; (4) Top 5 tree species in Hong Kong

## 5. Conclusions

In this paper, a review of measuring technologies on tree sway, tree tilt, and root-plate movement is presented. As an important part of urban ecosystems, urban forests can modulate urban microclimate and maintain biodiversity. However, urban trees are vulnerable and prone to tilt and uproot when exposed to external forces. To understand the mechanism of tree–wind interactions, methodologies on tree sensor monitoring were summarized. The specialty of inherent tree features is elucidated in terms of wood elasticity, the natural frequency of trees, damping ratio, and DBH. Sensors and instruments that can be utilized to measure the vertical displacement of trees provide various tilt measurements to detect the tilt displacement, yet these are greatly subject to the instrumental specifications. To investigate the dynamics of tree–wind interactions, field investigation can be carried out in natural wind load conditions, static pulling tests, and wind tunnel experiments. With a comparison of the three approaches, field measurements carried out in dynamic wind loading conditions are the most-used approach with a fast and simple set-up.

From the review of the pilot study, tree tilt measurement can be carried out in the time-space domain or the time-frequency domain. Time-space-based techniques focus on fundamental statistical analysis, ANOVA, and regression analysis to extract tilt-related information. Frequency-domain-based methods, on the other hand, mainly use wavelet

analysis and Fourier Transform to examine the sway frequency of tree and branch displacement. Among numerous tilt-related parameters, measures such as DBH, tree slenderness, tree elasticity, damping ratio, wind speed, and the root–soil system are considered as important indicators of tree sway, tilt movement, and root–plate displacement.

Discussions on the displacement measures of tree root and a comparison between conifer trees and broadleaf trees demonstrated that most of the tree–wind studies focus on conifer trees, while broadleaf (including both evergreen and deciduous) trees are seldom studied, and the sample size is relatively small, while it may be due to the lack of tree architecture data. Meanwhile, research methods on tree displacement have given the status of fully leafed or leafless for broadleaf trees which can have a huge effect on the modeling of tree–wind interactions.

Until now, an integrated monitoring system has not been developed to measure the tilt angle of a tree structural root zone being proposed for the identification of potential tree hazards. The existing literature shows fruitful results in analyzing possible factors that may cause tree failure, but the tree management over a wide variety of trees planted in the urban area lacks a practical demonstration platform. A pilot study of Hong Kong is introduced, showcasing an integrated tree tilting monitoring system based on smart sensing technology. SST sensors are progressively installed on 8000 trees for massive-scale monitoring. With a GIS-based platform to master the view of the locations and information of the trees on the map, this system is designed to modulate and predict potential tree hazards in urban areas. A dashboard including the map, the sensor and tree information, the alert, scenario-based setting, and the notification system, is developed with a user interface to observe the health status of trees in near real-time.

In the future, the research focus will be the enhancement of an integrated tree monitoring system, aiming at higher coverage of different tree species in Hong Kong, including the evergreen broadleaf trees that are seldomly investigated by research. The validity tests of trees and sensors are being carried out continuously within 8000 sample trees, and they deserve a further study for an in-depth understanding of the impact of wind load on the subtropical tree species through large-scale implementation and big data collection.

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