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Research Paper

Applying precision triaxial accelerometer to monitor branch sway of an urban tree in a tropical cyclone

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ABSTRACT

Trees are invaluable to urban landscape and environmental quality. However, tree failure can jeopardize life and property. Although the sway behavior of many coniferous species in temperate forest has been comprehensively evaluated, few studies have covered broadleaf tropical trees. This research aims at demonstrating the application of a new precision triaxial accelerometer to assess branch sway of an urban tree in tropical Hong Kong, testing the use of quantitative analysis to the large volume of generated sway and wind data, and identifying the factors influencing the branch sway behavior of the sampled tree. Following the tree selection criteria, four branches that are respectively healthy, crossed, wounded and hollow on a broadleaf deciduous *Delonix regia* (Flame of the Forest) were monitored by high-precision Tree Motion Sensors (TMS) during a tropical cyclone event. The results indicate significant inter-branch and axial difference in time-domain and frequency domain sway behavior. The average fundamental frequency of the branches ranged from 0.471 to 0.593 Hz. Mean sway amplitude (SA_{MEAN}) correlated the best with wind speed fluctuations (maximum $\rho = 0.801$). Scientific instrumentation and data processing, such as the SA_{MEAN} approach to monitor branch sway, can inform tree-risk management actions to abate possible failure. The approach undertaken in this study is an appropriate and effective means of monitoring tree sway and interpreting the associated data.

1. Introduction

Environmental sustainability in urban design is paramount in the face of urbanization and population rise (United Nations, 2015a,b). Urban trees can contribute to urban livability by providing multiple ecosystem services and nature-based solutions to achieve urban sustainability (European Commission, 2015). Trees can bring cooling to modify thermal sensation. For example, on average, under tree shade, air temperature, solar radiation and thermal comfort could change respectively by −9.5%, −94.9% and +5.6% in Thessaloniki, Greece (Georgi & Zafiriadis, 2006). A modelling study in Phoenix, Arizona, suggested a maximum monthly energy saving of US\$ 5.5 per m^2 of ground area covered by tree crown in August due to urban tree-induced cooling (Wang, Zhao, Yang, & Song, 2016).

The annual air pollutant removal by trees in Szeged, Hungary has been monetized at € 1–2 per tree (Kiss, Takács, Pogácsás, & Gulyás, 2015). Trees have been shown to provide psychological restorative benefits (Lindal & Hartig, 2015). Tree presence in urban squares has also been associated with increased aesthetic values, higher service prices in restaurants and a willingness of restaurant patrons to stay longer (Rašković & Decker, 2015).

However, urban trees often live under stressful conditions and are therefore susceptible to damage, mistreatment and structural weakness. Tree failure, e.g. branch and trunk breakage and uprooting, represents a risk to life and property, especially in times of strong wind. Understanding tree sway behavior using an in-situ approach can reduce tree failure and facilitate tree-risk management. Accurate measurement methods can generate high-quality data on tree sway magnitude and wind speed and direction for in-depth analysis. Such examples include laser beam systems (Baker, 1997), prism-based systems (Hassinen, Lemettinen, Peltola, Kellomäki, & Gardiner, 1998), strain meters (James & Kane, 2008), clinometers (Schindler et al., 2010), accelerometers (James, Hallam, & Spencer, 2013), and sonic anemometers (Schindler, Fugmann, Schönborn, & Mayer, 2012). But accelerometers and sonic anemometers were not commonly used together (Schindler, Fugmann, & Mayer, 2013).

Tree Motion Sensor (TMS, Argus Electronic GmbH, Rostock, Germany), a new high-precision triaxial accelerometer type of sensor, has been invented recently aiming specifically at improving the technique of monitoring tree tilt or sway motion. It has been put into

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practice in Australian tree-risk research, which focused on tree-pulling static tests (James & Hallam, 2013; James et al., 2013). The instrument's vast potential in accurately recording dynamic branch sway in wind, and its long-term deployment in harsh field conditions, are yet to be assessed by systematic research.

Sway behavior can be divided into the time-domain and frequency-domain types. Natural frequency (defined in Eq. (1) below), the preferred frequency at which a tree would tend to sway, is an important research focus because sway magnitude could enlarge rapidly at this frequency and lead to possible failure. Time-domain data analysis evaluates the bending motion of and the wind stress on a tree. Peltola, Kellomäki, Hassinen, Lemettinen, and Aho (1993) investigated the relationship among wind speed, wind direction and swaying behavior. They found limited sway behavior variations in direction relative to wind speed. Kane, Pavlis, Harris, and Seiler (2008) suggested that tree-care practitioners can assess trunk-failure risk by examining the critical wind speed of trunk failure and the maximum tolerable loss of cross-sectional area to wood decay. Schindler (2008) proposed the importance of short-lived gusts in determining tree displacement, i.e., the degree of swaying in response to energy transfer from wind to tree. Under high prevailing wind speed, intermittent pulses of wind-speed increase could induce the greatest tree displacement.

Time-domain data can be converted into frequency-domain. The frequency of oscillatory motion can be computed by:

$$f = \frac{1}{T} \tag{1}$$

where frequency (f) is the reciprocal of period (T). At the natural frequency (f_N), the transfer of energy from wind to tree is efficient, so the resulting sway motion is of a notably high amplitude. The energy transfer at f_N can endanger tree stability by creating resonance, which is fostered by pulses of wind-speed increase arriving at a frequency near the f_N (James, 2003). Resonance refers to the phenomenon in which wind as a force amplifies tree sway as oscillation motion at a particular frequency which could be f_N. When resonance occurs, the absorbed energy can quickly increase the magnitude of tree displacement. The exerted force may reach a threshold called the critical bending moment above which tree may fail. Some studies investigated the factors related to f_N. For instance, Kane and James (2011) and Moore and Maguire (2005) confirmed the positive relationship between slenderness as expressed by DBH:H^2 (diameter at breast height to tree height squared) and f_N. Baker (1997) found higher f_N in diseased trees. Ciftci, Brena, Kane, and Arwade (2013) identified that DBH, branch slenderness, elasticity of stems and branches and damping ratio as factors influencing sway.

Most studies used coniferous species common to the temperate latitudes, such as *Picea sitchensis* (Milne, 1991), *Pinus contorta* (Rudnicki, Silins, Lieffers, & Josi, 2001) and *Pinus sylvestris* (Schindler et al., 2013). Less research investigated tropical broadleaf deciduous or evergreen species, especially specimens in urban settings (Baker & Bell, 1992; Roodbaraky, Baker, Dawson, & Wright, 1994). As branch snapping is a common mode of tree failure, the topic deserves in-depth exploration, especially in dense urban areas where life and property are vulnerable to the failure of trees under stressful growing conditions.

The objectives of this study are: (1) to test the TMS method by assessing branch-sway behavior of an urban tree in the tropical region in response to exceptionally strong wind of a tropical cyclone; and (2) to apply quantitative techniques to analyze the large volume of data generated by the monitoring instruments; and (3) to identify the factors influencing branch sway behavior based on the interpretation of the results. This study could demonstrate the usefulness of the TMS method for the management of risks associated with urban tree failure during strong wind.

2. Methods: Experimental design

2.1. Study area

Hong Kong (22°N, 114°E) faces a humid sub-tropical climate with hot-humid summer and cool-dry winter (Hong Kong Observatory, 2015). The 30-year period (1981–2010) monthly mean temperature ranged from 16.3 °C in January to 28.8 °C in July. The 30-year normal annual rainfall is 2398.5 mm, with nearly 79% falling during May to September. Under the summer monsoon influence, tropical cyclones (known as typhoons in the region) bring ample rains and maximum sustained wind speed above 118 km/h near the center of tropical cyclone. In September, monsoon influence resulted in a monthly mean wind speed of 11.4 km/h and a monthly rainfall of 327.6 mm.

Hong Kong is an exceptionally high-density city due to shortage of easily developable land (Census and Statistics Department, 2017). The 7.4-million population is living in about a quarter of the total land area of 1108 km^2. Trees growing in areas of high building and population density could impose high risk to people in case of tree failure, and demand effective preventive measures.

2.2. Selection of sampled tree and sampled branches

A reconnaissance survey in 2014 identified a sampled tree for detailed monitoring of sway based on the following selection criteria: (a) Location in developed sites or roadsides in built-up areas; (b) Attainment of at least 50% final tree height and a crown with a sizeable sail area; (c) Maximum tree height of 10 m; (d) Common urban-tree species; (e) Planted in open soil; and (f) Different kinds of defects on major branches.

The "sampled tree" serving as the research subject was a *Delonix regia* (Flame of the Forest) (Fig. 1) with a size close to its biological potential given the physical constraints (especially soil volume limitation) and physiological stresses of the urban site (Jim, 1998), denoting a typical urban tree in the local context. The characteristic parasol-like broad crown and key dimensions are shown in Fig. 1b.

Four branches among which three carried different kinds of defects were monitored (Fig. 2). Healthy, crossed, wounded, and hollow branches along with their positions and dimensions are depicted in Fig. 2b. The healthy branch without physical defects served as a reference baseline. The crossed branch was in physical contact with another unsensored branch of the same order and similar dimensions. They would rub against each other during sway in response to wind. The wounded branch had a debarked stretch with weakened wood. The cavity of the hollow branch, housing an ant community, had a relatively upright orientation compared to other branches.

Given the evaluation of only four branches on one tree, the results would be inappropriate for generalization but possible for demonstrating with a real-world case the instrumental monitoring of sway and the techniques of analyzing and interpreting the generated data.

2.3. Instrumentation and data acquisition

The high-precision TMS boasts the following advantages:

- High angular resolution: 0.01°
- High sampling frequency: 20 Hz
- Fast response time: 400 ms

Three sensors were included in a triaxial configuration (Fig. 3a) in one integrated tubular case instead of using three separate instruments, as were used in the past. With TMS, all three sensors, data-logger and magnetic controller are housed in a compact cylindrical (10 cm long × 4.4 cm diameter), weather-proof and durable aluminum shell. The built-in rechargeable power supply allows continuous operation for 20 days. The girdle mount permits simple installation using two