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Non-oscillatory response to wind loading dominates movement of Scots pine trees

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ABSTRACT

The response of four trees in a Scots pine (*Pinus sylvestris* L.) plantation to wind loading was studied using time series decomposition methods. For this purpose, wind speed and stem displacement time series recorded on a windy day were divided into intervals adjusted according to stem displacement. The real wind load acting on the sample trees during the intervals was estimated by the momentum flux at canopy top. To identify components in wind-induced stem displacement that are correlated with the wind, wavelet coherence was calculated. Results from these calculations indicate that the trees mainly responded to wind components with periods longer than their damped fundamental sway periods. Therefore, stem displacement data were decomposed into non-oscillatory and oscillatory components as well as noise using singular spectrum analysis. Results from singular spectrum analysis demonstrate that with increasing momentum flux, the importance of oscillatory components in the stem displacement time series decreases whereas the importance of non-oscillatory displacement components increases. The decreasing importance of the oscillatory components suggests that wind loading in the range of the damped fundamental sway period of the trees is inefficient and insignificant for total tree movement under non-destructive wind conditions. Consequently, there was no evidence of the occurrence of resonance effects between wind and tree response.

1. Introduction

Dynamic responses of conifers to wind loading are complex since near-surface airflow simultaneously acts on all aerial tree parts at various temporal (tenths of seconds to minutes) and spatial (needles to stem) scales (de Langre, 2008). Results from previous field studies on the instantaneous response behavior of conifers to non-destructive wind loading indicate that wind-induced tree movement is dominated by damped bending sways (Gardiner, 1994; Mayer, 1987; Schindler et al., 2010; Sellier et al., 2008) similar to the vibrational dynamics of a damped harmonic oscillator (Flesch and Wilson, 1999; Gardiner, 1992, 1995). It is commonly accepted that sway in the range of the damped fundamental sway frequency makes up a large part of total tree response under low wind conditions. Schindler et al. (2013a) reported for five neighboring trees growing in a planted Scots pine (*Pinus sylvestris* L.) forest that under conditions where hourly mean wind speed at canopy top was below 2.5 m/s, sway in the fundamental mode at frequencies of 0.25–0.45 Hz dominates total tree response to wind excitation. Similar results on the response behavior of two Maritime pine (*Pinus pinaster* Ait.) trees to wind excitation can be found in Sellier et al. (2008).

One option for the simulation of wind-induced stem sway of conifers is using the damped harmonic oscillator equation. The movement of a multiple-degree-of-freedom stem may be calculated as (de Langre, 2008):

$$M\ddot{d} + C\dot{d} + Kd = WL(t) \tag{1}$$

where M is the mass matrix, C is the viscous damping matrix, K is the stiffness matrix, WL is the time-varying wind load vector, and $d, \dot{d}, \ddot{d}$ are stem displacement, stem velocity, and stem acceleration. The wind load acting on a conifer may be estimated using (de Langre, 2008):

$$WL(t) = 0.5\,\rho\, C_{drag}\, FA\, |u-\dot{d}|(u-\dot{d}) \tag{2}$$

where ρ is air density, C_{drag} is the drag coefficient, FA is the frontal area of the crown perpendicular to the airflow, and u is the streamwise wind speed.

Although Eqs. (1) and (2) basically allow for the simulation of wind-tree interactions, uncertainties in the wind load estimation arise from various sources that are part of total tree movement damping. Both C_{drag} and FA are functions of the local wind speed and vary instantaneously (Hedden et al., 1995; Rudnicki et al., 2004). Moreover, C_{drag} substantially varies among different tree species as well as within the same

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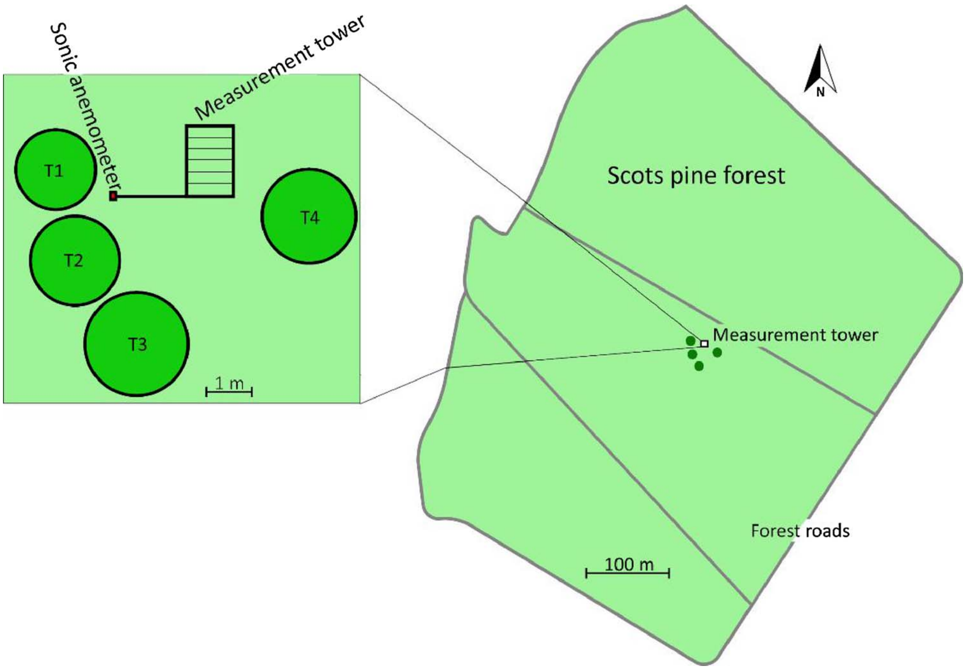

Fig. 1. Study site with measurement tower and spatial arrangement of the four sample trees (T1–T4). The black circles indicate the mean crown radii of the sample trees at zero-plane displacement height (z/h_s= 0.78).

tree species (Mayhead, 1973). Until today, generalizable descriptions of the variability of C_{drag} and FA under real wind conditions are still unavailable. Further sources of uncertainty in mechanistic wind-tree interactions modeling not explicitly addressed in Eqs. (1) and (2) arise from incomplete knowledge of (1) crown interactions with neighbor trees (Milne, 1991; Rudnicki et al., 2001, 2003, 2008; Webb and Rudnicki, 2009), (2) viscous damping of the wood (Brüchert and Gardiner, 2006; Milne, 1991), (3) root anchorage as a function of soil moisture (Mayer, 1987), and (4) damping associated with multimodal vibration behavior of stem and branches (Gardiner, 1995; Rodriguez et al., 2008; Spatz et al., 2007).

Analysis of the dynamics of wind-tree interactions requires the application of spectral methods such as Fourier analysis (Mayer, 1987) or wavelet analysis (Schindler, 2008; Schindler et al., 2010) to gain deeper insight into the response behavior of conifers to wind loading. Up to now, analysis in the time domain does not provide physically interpretable results. Of special interest is the frequency range in which kinetic energy transfer from the wind into tree movement is most efficient. Results from the application of Fourier transform-based mechanical transfer functions (Mayer, 1987) suggest that conifers absorb considerable amounts of kinetic energy contained in the wind in the range of their damped fundamental sway frequency (Gardiner, 1992, 1994, 1995; Schindler, 2008; Schindler et al., 2012, 2013a; Sellier et al., 2008).

Although sway in the fundamental mode is important for tree movement under low wind conditions, there is debate about the range for the excitation frequencies of wind-induced tree responses. It is clear that trees oscillate at their damped natural frequencies under free vibration that can be simulated by tree pulling tests (Peltola et al., 2000). The damped natural frequencies are the frequencies at which resonance effects will occur if trees are excited at these frequencies (Moore and Maguire, 2004). Schindler et al. (2010, 2013a), however, speculated that absorption of kinetic energy available from the wind in the range of the damped fundamental and higher order sway frequencies is of minor importance for total stem displacement. Instead, wind-induced stem displacement is initially caused by wind components occurring at frequencies below the damped fundamental sway frequency of stems of the studied Scots pine trees.

To the best of the authors' knowledge, there are no results from field studies which provide evidence that wind loading in the range of the damped fundamental and higher order sway frequencies drives total tree movement under low wind conditions. Moreover, data from field measurements of instantaneous forest tree responses to high wind loading are still rare, preventing a comprehensive analysis of tree responses to wind over the entire range of non-destructive wind conditions. Based on the complex and complicated nature of wind-tree interactions and current scientific knowledge, it is still challenging to model wind-induced responses of conifers under real wind conditions with any process-based approach.

Therefore, this paper reports on a further attempt to advance knowledge on responses of Scots pine trees to non-destructive wind loading using time series decomposition methods. Differences to previous studies are the occurrence of higher wind speed during the selected analysis period and a refined approach for the segmentation of the analyzed data. The chosen segmentation approach better accounts for wind-tree interactions because it separates windy from calm episodes instead of using fixed length intervals during which windy and calm episodes are often mixed. The main objective of the present study is the identification and separation of important components in tree movement that actually respond to wind excitation. The dynamics of these components are then described as a function of the wind load at canopy top estimated by the momentum flux.

2. Material and methods

2.1. Airflow and stem displacement measurements

The measurement site is located in a planted Scots pine (*Pinus sylvestris* L.) forest in the southern Upper Rhine Valley (47°56′04″N, 7°36′02″E, 201 m above sea level). The forest was established in the 1960s with 2-year-old saplings. During the measurement period between 14 January 2016 and 8 April 2016, the Scots pine forest around the measurement site had a mean stand density of 580 trees per hectare and a mean stand height (h_s) of 18 m. At the measurement site, five ultrasonic anemometers (R.M. Young Company, USA, Type 81000VRE) mounted on a 30 m high scaffold tower, routinely measure (sampling rate 10 Hz) wind vector components in x (u), y (v), and z (w) direction within and above the Scots pine forest at 2 m (z_1/h_s = 0.11), 9 m (z_2/h_s = 0.50), 18 m (z_3/h_s = 1.00, canopy top), 21 m (z_4/h_s = 1.15), and 30 m (z_5/h_s = 1.67) above ground level. Since airflow from northern