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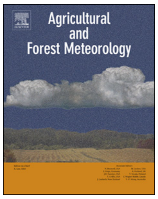

Evaluation of the drag coefficients of tree crowns by numerical modeling of their free fall

S.A. Borisevich[*], V.S. Vikhrenko

Belarusian State Technological University, 13a, Sverdlova str., 220006 Minsk, Belarus

A R T I C L E   I N F O

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A B S T R A C T

The method for evaluation of wind loads and drag coefficients for the trees of different species, size and morphology in natural conditions that does not require special equipment is presented for the first time. Field experiments and numerical simulation were performed for five trees of the Scots pine trees (*Pinus sylvestris* L.) under free fall. The field experiments were carried out in the forest for symmetrical 23–27 m tall pine trees. The trees were cut by the chainsaw operator and the videos of a tree falling were obtained. Still images were captured from the video every second after the start of movement. Then the tree stem center lines from the images were obtained. After each run, the length and diameter of the stem and the geometrical characteristics of the tree crown were checked. Numerical experiments were carried out using the deformation model of the tree stem that is inspired by the Cosserat theory of elastic rods. Under the assumption that the drag force is distributed along the tree stem according to a triangular load and increases linearly with velocity, the dynamic global behavior of the real trees was reproduced and the tree stem center lines were obtained. By comparing the data of the two experiments, the drag coefficients of the whole pine trees were found.

1. Introduction

There are many problems connected with mechanical interactions between wind and plants. A review of the large variety of mechanical interactions between wind and plants, from plant organs to plant systems, can be found in Gardiner et al. (2016) and Langre (2008). More fundamental biological and technical issues have created the need for data and models of wind-plant mechanical interactions. The studies determining the mechanical interactions between wind and plants are of great practical importance. The results of these studies can be used to understand tree susceptibility to wind damage and the effects of wind on the essential functions of a plant. Not all problems can be completely solved without knowledge of the wind load acting on the tree crown. Although wind load has been measured on parts of trees in wind tunnels (Mayhead, 1973; Vollsinger et al., 2005; Orlov and Shrager et al., 2011; Rudnicki et al., 2004), full trees have not been considered, because of the difficulty of outdoor measurements.

Wind causes local skin friction and pressure drag on a plant surface. The conventional formula for drag load, *F*, in the direction of wind flow on a bluff body such as a tree crown placed in a steady airstream is

$$F = \frac{1}{2}\rho A C_d v^2, \tag{1}$$

where C_d is the dimensionless drag coefficient that depends on the geometry and the Reynolds number, ρ is the air density, *A* is the frontal area of the trunk and crown, and *v* is the wind velocity. This conventional form is based on Newton's laws of motion and widely used in the scientific and engineering literature. It is explained in detail in Niklas (1992) and Vogel (1994). Eq. (1) assumes the drag induced by wind varies as the square of *v*. It has often been reported that the v^2 variation of drag does not apply to plants. This has been expressed in terms of a Vogel exponent, noted *b*, so that the dependence of drag load on velocity scales as v^{2+b}, and. $b = -1$ frequently appears in experimental studies. Mayhead (1973) working with conifer data in wind tunnel tests reported that "drag is found to vary linearly with wind speed (*v*), and not with v^2" . In fact, much earlier sources observed the same behavior. The results for drag load on cedar pine branches (Orlov and Shrager et al., 2011) show a linear dependence on velocity. In the article Smiley et al. (2000), wind loads on the green trees were measured at various wind speed. They reported that drag load showed a linear increase with wind speed as well. More information can be found in Cullen (2005). Thus, the value of $b = -1$ is not uncommon and so we can adopt that the drag load increases linearly with the velocity. Most observations relate this reduction to significant deformations of the plant that fall under the generic name of reconfiguration [Vogel, 1989]. It is an essential mechanism by which vegetation reduces stress induced by

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[*] Corresponding author.
E-mail address: borsera@mail.ru (S.A. Borisevich).

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external flow, in air or water (Harder et al., 2004). For a nonporous body, flow-induced deformation may affect drag through two distinct mechanisms. First, as noted by most authors, deformation induces a reduction in the effective cross-flow area, A, which directly reduces the total drag load. Second, the deformed shape may be more streamlined, so the pressure recovery in its wake is improved, also reducing drag. These combined effects are fully discussed in Vollsinger et al. (2005) for a tree crown in a wind tunnel.

A number of authors have used Eq. (1) for calculating drag load on trees. The approach to dealing with C_d and frontal area A varies. Some authors use still-air frontal areas and wind-speed-specific static C_d values [Mayhead, 1973]. Others use constant C_d values and estimate the reduction in frontal area with increasing wind speed (Smith et al., 1987; Peltola and Kellomäki, 1993; Hedden et al., 1995; Spatz and Bruechert, 2000). In either approach, it is preferable to begin with empirical measurements of the drag and frontal area. However, there are very few studies in which these values are reported. Conducting a literature review of experimental works, we find that with increasing wind speed both frontal area of the tree crown and drag coefficient are reduced. However, if we calculate the product $AC_d v/2$ based on the experimental data we can find that this product is approximately constant. This is true for the whole tree crown (Mayhead, 1973; Rudnicki et al., 2004; Vollsinger et al., 2005) and for an element of the tree crown (Orlov and Shrager et al., 2011). Therefore, it can be assumed that the drag load increases linearly with the velocity and has the form

$$F = \beta v, \tag{2}$$

where β is the scaling parameter measured in kg/s that does not separate the reference area A and drag coefficient C_d, as only their combined effect matters.

The measurement of the drag coefficient in wind tunnel leads to a number of difficulties. It is impossible to deal with actual trees due to their large size and all past investigations have been performed with small trees or a part of the crown cutting it to a size suitable for the wind tunnel. The objective of the current study is to propose a new method to investigate wind load on trees by comparing the results of a field experiment and numerical simulation of the tree free fall. The method can be applied to trees of different species, size and morphology, and does not require special equipment.

2. Materials and methods

The sampling was restricted to symmetrical, 23–27 m tall trees samplings of the Scots pine (*Pinus sylvestris* L.) that grew up in the forest with more or less closed canopy, 100 km south of Minsk, Belarus. As a result of the crowded growing conditions, canopy trees only branch near the top of their long, pole-like trunks. Five trees were cut by a chainsaw operator applying the basic principles for safe, directional tree felling. The general features are an open notch, a felling cut and a residual wood strip between the two cuts (Fig. 1). The felling cut and the bottom of the notch are assumed to be level with each other. The residual wood strip is called the hinge, since the term reflects its main function. The thickness of the hinge ranges from a minimum of 1 cm to a relative measure of 10% of the tree's diameter at a breast height. Since the hinge is not located in the vertical of the stem center, the gravitational force acting through the centre of gravity of even a completely straight tree and the hinge's bending resistance will counteract movement in the intended falling direction and additional force will be required to overcome them. A long pole was used to start the motion and the fall proceeds without added force when the center of gravity is sufficiently far towards the notch side of the hinge.

A video camera was installed at a distance of 20 m from the tree so that the camera axis is considered perpendicular to the expected plane of movement of the tree. The fall of each tree was filmed on the video camera (model Nikon Coolpix S8200, Nikon Corporation, Japan). After each run, we checked the length and diameter of the tree stem and the geometrical characteristics of the tree crown. The volume of the tree stems was obtained from their length and diameter and the mass was found as the product of volume multiplied by density. The density of the stem was not measured for each tree and it is assumed to be 780 kg/m^3 as an average density for green pine wood. In fact, the value of the density may vary depending on growth conditions and season, but averages typically range from 710 to 850 kg/m^3 for the Scots pine in summer (Tomczak and Jelonec, 2014).

Still images were captured from the video every second after the start of movement. To prevent possible errors caused by lens distortion, we fixed perspective image errors with the Adobe Photoshop (Adobe Systems, San Jose, USA) software using the lens correction filter. The tree stem center lines were obtained from the digital images using the same software (Fig. 2). The image scale was established as the ratio of the image length of the tree to its actual length.

Numerical experiments were carried out using the deformation model of the tree stem that is inspired by the Cosserat theory of elastic rods. This theory is well investigated in the field of nonlinear elasticity. A comprehensive discussion of the topic is given in Antman (1995). Actually, the tree stem can be thought of as a three-dimensional long and thin deformable rod undergoing large displacements and deformations under the influence of gravity and air resistance of the tree crown that is rotated around a fulcrum, located in the middle of the hinge. This model is somewhat similar to that considered in the paper of Kerzenmacher and Gardiner (1998) which has been used to describe the dynamic response of a spruce tree to the wind. In the latter, small deflections from the vertical line are considered, and it cannot be applied to investigate the tree fall. Some authors used more simple static method to perform the calculation of deflected shape for a vertical cantilever (Neild and Wood, 1999). The method is based on ordinary differential equations and it is not suitable for studying the dynamics of motion of a tree under free fall, which requires integration of differential equations in partial derivatives and special difference schemes.

We represent the centerline $r(s)$ of the tree stem as a chain of n

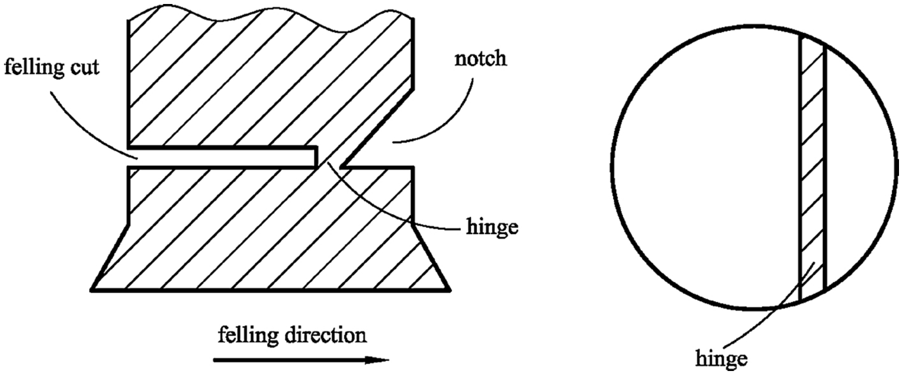

Fig. 1. Schematic diagram of a tree stump and typical felling cut features; (left panel – side view, right panel – top view.