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Drag and wake of a tree in the wind: laboratory experiments, field measurements, and numerical simulations

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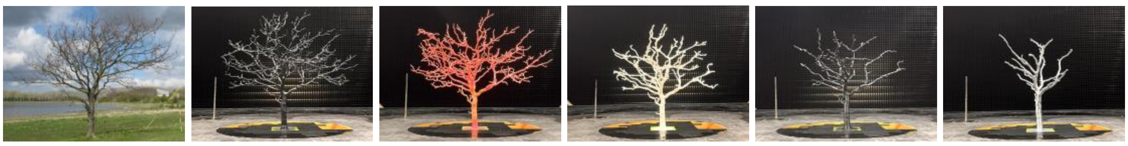
This study explores the influence of geometric detail on the drag force acting on a tree of realistic architecture. Combining wind tunnel experiments, field data, and numerical simulations, the study aims to deepen our understanding of how the drag force and drag coefficient are affected by varying fidelity levels of the model's branching structure. The overarching goal is the improvement of high-resolution wind resource assessment and urban planning models.

The tree models have been reconstructed from terrestrial laser scans of a 6.8 m tall oak tree in its leaf-less state, located at the Roskilde Fjord in Denmark (Figure 1a). The drag force and the drag coefficient on the natural tree were estimated using calibrated strain gauges, mounted on the lowermost part of the stem[1]. Wind tunnel experiments were conducted at ETH Zurich using 3D-printed models of the tree, scaled down by a factor 13.6. A series of models is considered, with the smallest branch diameters systematically truncated at 2, 2.5, 3, and 4 cm thresholds (full-scale dimensions, Figure 1b-1f). Aerodynamic forces and moments on the models were measured by mounting them on a six-component force sensor.

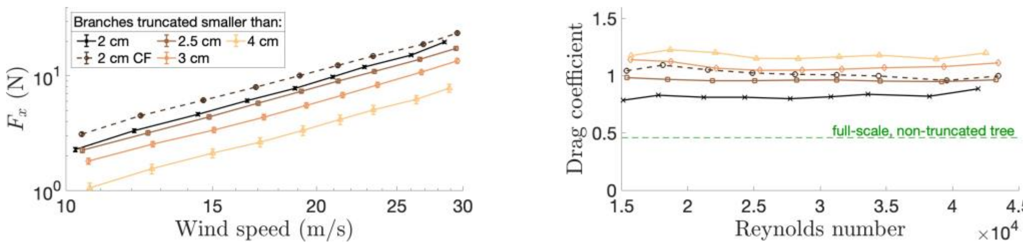
Figure 2a shows the observed quadratic relationship between drag force and velocity across all models, with greater geometric detail leading to higher forces. Although most models were printed from polylactic acid (PLA), one model (2 cm CF) is constructed from a stiffer carbon fiber-reinforced PLA, showing the potential influence of material properties and minor geometric variations on the results. For the drag coefficients, frontal areas have been determined via image processing. The frontal area is used to define the drag coefficient. A consistent trend of increasing drag coefficients with higher levels of branch truncation is observed (Figure 2b), while no dependency with Reynolds number is observed within the considered range. When compared to the drag coefficient of the full-scale, non-truncated tree, an alignment with the trend of decreasing drag coefficients for more detailed tree geometries is evident. While the drag coefficient of the full-scale leaf-less tree has been determined for a different Reynolds number range, it also exhibited no Reynolds number dependency.

The study's findings are supplemented by time-resolved Particle Image Velocimetry experiments and by simulations using the immersed boundary method, providing further insights into the near-wake flow.



(a) Oak tree. (b) 2 cm CF. (c) 2 cm. (d) 2.5 cm. (e) 3 cm. (f) 4 cm.

Figure 1: (a) Oak tree located on DTU's Risø campus. (b)–(f) Scaled and 3D-printed models of the oak in the wind tunnel with a systematic variation of the truncation threshold for branch diameters.



(a) Mean drag forces in the flow direction (dots) with standard deviations (error bars).

(b) Drag coefficients; Reynolds number based on the stem diameter at breast height.

Figure 2: Wind tunnel measurement results for wind speeds from 10 to 30 m/s.

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[1] Angelou et al., *Journal of Wind Engineering and Industrial Aerodynamics* **257**, 105966 (2025)