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Large coupled bending and torsional deformation of an elastic rod subjected to fluid flow

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ABSTRACT

In the present work, we seek to understand the fundamental mechanisms of three-dimensional reconfiguration of plants by studying the large deformation of a flexible rod in fluid flow. Flexible rods made of polyurethane foam and reinforced with nylon fibers are tested in a wind tunnel. The rods have bending–torsion coupling which induces a torsional deformation during asymmetric bending. A mathematical model is also developed by coupling the Kirchhoff rod theory with a semi-empirical drag formulation. Different alignments of the material frame with respect to the flow direction and a range of structural properties are considered to study their effect on the deformation of the flexible rod and its drag scaling. Results show that twisting causes the flexible rods to reorient and bend with the minimum bending rigidity. It is also found that the Vogel exponent of a reconfiguring rod is not affected by torsion. Finally, using a proper set of dimensionless numbers, the state of a bending and twisting rod is characterized as a beam undergoing a pure bending deformation.

1. Introduction

In contrast to engineering structures, plants are generally flexible and deform significantly under fluid loading. This deformation typically causes drag reduction and is called *reconfiguration* in biomechanics (Vogel, 1984, 1989). Unlike rigid bluff bodies, the drag force on plants is not proportional to the square of the flow velocity. The drag force on flexible plants varies with the flow velocity as

$$D \propto U^{2+\vartheta}, \tag{1}$$

where ϑ is the Vogel exponent. This exponent quantifies the effect of flexibility on the drag scaling and is typically negative for plants (Vogel, 1984). Plants reconfigure using two main mechanisms: frontal area reduction and streamlining. The more negative ϑ is, the more the drag is reduced due to reconfiguration.

Many experimental drag measurements have been performed on trees (Vollsinger et al., 2005), crops (Sterling et al., 2003) and algae (Koehl and Alberte, 1988) whether in wind tunnels, water flumes or their natural setting. This was done to quantify the effect of streamlining and frontal area reduction on drag scaling. Understanding reconfiguration is necessary to predict or prevent the adverse effect of strong winds or water flows on plants such as windthrow, uprooting and lodging (Rudnicki et al., 2004; Berry et al., 2004). *Thigmomorphogenesis*, or the influence of mechanical stimuli such as wind loading

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Table 1
The average of twist-to-bend ratio for some natural and engineering structures.

Species	Geometry	η	Reference
Isovolumetric material	Circular	1.5	–
Metallic rod	Circular	1.3	–
Daffodil stem	Semi-circular	13.3	Vogel (2007)
Banana petiole	U-shape	68	Ennos et al. (2000)
Sedge stem	Semi-triangle	65	Ennos (1993)
Tree trunk	Semi-circular	7.34	Vogel (2007)

on the growth of plants, is another area where a better understanding of plant–flow interaction can make a contribution (Niklas, 1998).

In general, plants are slender and a fundamental understanding of their reconfiguration has therefore been sought by modeling them as bending beams and plates (Alben et al., 2002, 2004; Gosselin et al., 2010; Luhar and Nepf, 2011; Gosselin and de Langre, 2011; Schouveiler and Boudaoud, 2006). A flexible beam undergoing bending due to flow is a simple academic representation of reconfiguration. For instance, the deformation and the drag of flexible glass fibers have been measured in a two-dimensional soap film flow which allows modeling and flow visualisation (Alben et al., 2002, 2004). To theoretically model the bending fiber in the soap film flow, the authors coupled the Euler–Bernoulli beam theory with an exact potential flow solution using the Helmholtz free streamline theory. Bending plates made of transparency films were also studied in a wind tunnel (Gosselin et al., 2010). Theoretical representation of these experiments was done by coupling a semi-empirical drag formulation and the Euler–Bernoulli beam theory.

Although bending beams and fibers capture the essence of the two-dimensional deformation of plants, they cannot represent all forms of reconfiguration. Other effects are important in reconfiguration and can influence the Vogel exponent such as buoyancy (Luhar and Nepf, 2011), poroelasticity (Gosselin and de Langre, 2011), three-dimensional bending deformation (Schouveiler and Boudaoud, 2006). Moreover, the approach of using simple structures was also employed to study inelastic brittle reconfiguration, i.e., pruning (Lopez et al., 2011; Eloy, 2011).

While the aforementioned fundamental studies focus on bending deformation, torsion has been ignored in reconfiguration. However, it is known that plants twist significantly under fluid loading. For instance, the stem of a daffodil holds the flower horizontally and twists at the slightest breeze aligning the flower downwind thus reducing its drag (Etnier and Vogel, 2000). The trunks of trees with crown asymmetry also undergo significant twist under wind loading. Because of their fibrous construction, plants and trees are known to twist more easily than they bend (Vogel, 1992; Skatter and Kuera, 1997). This is quantified by the *twist-to-bend ratio*,

$$\eta = \frac{EI}{GJ}, \tag{2}$$

where EI is the bending rigidity and GJ is the torsional rigidity. High values of η represent a structure which can twist more easily than it can bend. Table 1 shows a comparison between the twist-to-bend ratios of some natural and engineering structures.

In comparison to engineering structures, branches, petioles and stems have a significantly larger value of η (Vogel, 1992; Pasini and Mirjalili, 2006). Fig. 1a shows a schematic of the U-shape cross section of a banana petiole with a large twist-to-bend ratio of 68. As a result, a banana leaf twists while bending downwind (see Fig. 1b and c). For comparison, a homogeneous and isotropic material with circular section has a twist-to-bend ratio equal to $1+\nu$ or 1.3 for metallic materials assuming that Poisson's ratio is about 0.3 (Vogel, 1992).

Since many plants twist when subjected to flow, the following question arises: What is the effect of torsional deformation on the reconfiguration of plants and flexible structures, and how does it change their drag scaling, i.e., their Vogel number? The bending beams and plates of the previous studies cannot represent the torsional deformation of plants. Therefore a new approach is necessary to idealize plants with simple structures. In this paper, we consider the reconfiguration of an elastic rod which can twist and bend. A mathematical model is developed considering the arbitrary large deformation of a rod subjected to fluid flow. Tests are also done in a wind tunnel on flexible rods made of polyurethane foam with strategically placed reinforcements to tailor their twist-to-bend ratio and their twisting–bending coupling.

2. Methodology

2.1. Experimental procedure and materials

The large deformation of a flexible rod bending and twisting under pressure drag is studied. The tests are performed in the closed-loop wind tunnel of the laboratory of Aerodynamics and Fluid–Structure Interactions at École Polytechnique de Montréal. The wind tunnel has a square test section of $60 \times 60\ \text{cm}^2$ and can produce a maximum air speed of $90\ \text{m s}^{-1}$. Fig. 2 shows the custom-made load measuring equipment used for the wind tunnel tests. The test setup consists of a force balance (3), a speed reduction gearbox (2), and a rotary servo motor (1) mounted on the gearbox. The 6-axis force balance