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Wave-induced dynamics of flexible blades

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ABSTRACT

In this paper, we present an experimental and numerical study that describes the motion of flexible blades, scaled to be dynamically similar to natural aquatic vegetation, forced by wave-induced oscillatory flows. For the conditions tested, blade motion is governed primarily by two dimensionless variables: (i) the Cauchy number, Ca, which represents the ratio of the hydrodynamic forcing to the restoring force due to blade stiffness, and (ii) the ratio of the blade length to the wave orbital excursion, L. For flexible blades with $Ca \gg 1$, the relationship between drag and velocity can be described by two different scaling laws at the large- and small-excursion limits. For large excursions ($L \ll 1$), the flow resembles a unidirectional current and the scaling laws developed for steady-flow reconfiguration studies hold. For small excursions ($L \gg 1$), the beam equations may be linearized and a different scaling law for drag applies. The experimental force measurements suggest that the small-excursion scaling applies even for intermediate cases with $L \sim O(1)$. The numerical model employs the well-known Morison force formulation, and adequately reproduces the observed blade dynamics and measured hydrodynamic forces without the use of any fitted parameters. For $Ca \gg 1$, the movement of the flexible blades reduces the measured and modeled hydrodynamic drag relative to a rigid blade of the same morphology. However, in some cases with $Ca \sim O(1)$, the measured hydrodynamic forces generated by the flexible blades exceed those generated by rigid blades, but this is not reproduced in the model. Observations of blade motion suggest that this unusual behavior is related to an unsteady vortex shedding event, which the simple numerical model cannot reproduce. Finally, we also discuss implications for the modeling of wave energy dissipation over canopies of natural aquatic vegetation.

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1. Introduction

From salt-marshes to seagrass beds and kelp forests, flexible vegetation is ubiquitous in wave-dominated coastal zones. In all of these systems, the physical interaction between the wave-induced flow and the plants plays an important role in mediating geomorphological, biological and chemical processes. For instance, the drag generated by the plants leads to a dissipation of wave energy and a damping of the near-bed flow (Kobayashi et al., 1993; Lowe et al., 2005; Luhar and Coutu, 2010), which inhibits sediment suspension and transport. The resulting low-flow environment serves as habitat for many species of fish, shellfish and other aquatic organisms. The physical fluid–structure interaction also determines the posture and motion of the plants. In addition to influencing light availability (Zimmerman, 2003), plant posture and motion mediate

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nutrient uptake (Hurd, 2000; Huang et al., 2011) and oxygen efflux (Mass et al., 2010), which are some of the most important ecological services provided by aquatic vegetation (Costanza et al., 1997).

Because of its importance to coastal protection, wave energy dissipation over aquatic vegetation has received significant attention in the literature. It has been studied in the laboratory (Fonseca and Cahalan, 1992; Kobayashi et al., 1993; Manca et al., 2012), in the field (Bradley and Houser, 2009; Orfila et al., 2012), and using analytical methods or numerical models (Kobayashi et al., 1993; Mendez et al., 1999; Mendez and Losada, 2004). Unfortunately, an accurate prediction of wave attenuation is complicated by the fact that it requires knowledge of the dynamics of the plants. It is widely recognized that the rate of energy dissipation at the scale of individual plants depends on the relative motion between the fluid and the vegetation. Yet, there is no universally-accepted methodology to predict or account for vegetation motion. As a result, most studies thus far have been restricted to employing bulk drag coefficients that are calibrated to the observations [see e.g. Mendez and Losada, 2004; Bradley and Houser, 2009; Manca et al., 2012].

Several papers have proposed simple models for vegetation motion under wave-forcing to predict the hydrodynamic forces experienced by the plants and quantify the rate of wave energy dissipation. For example, Mendez et al. (1999) assumed that the flexible vegetation can be modeled as flat stems hinged at the base (i.e. linearly varying deflection with height) whose motion depends on the hydrodynamic forces. Mullarney and Henderson (2010) developed an analytical model to predict the motion of single-stem vegetation, showing that vegetation motion depends on a dimensionless parameter representing the ratio of the hydrodynamic drag and vegetation stiffness. This analytical model accounts for plant motion and morphological variations along the entire length of the stem. However, it is also restricted to small stem deflections (i.e. linearized Euler-Bernoulli beam theory), and does not include the effects of vegetation buoyancy or inertial effects such as added mass. In a recent numerical and experimental study, Zeller et al. (2014) developed a more complete model capable of simulating finite-amplitude deflections while accounting for drag as well as added mass. This effort indicated that the drag generated by the vegetation depends strongly on the ratio of the blade tip excursion to the wave orbital excursion. Recognizing that this ratio is not a practical predictive tool since it requires knowledge of the blade motion, Zeller et al. (2014) also developed a simple algebraic model that was fitted to numerical results in order to predict wave attenuation.

The purpose of the present study is to build on these previous efforts and improve our understanding of the wave-induced dynamic of flexible blades, with the ultimate goal being a simple, predictive framework to account for blade motion in wave energy dissipation models. Like Zeller et al. (2014), we pursue a combination of numerical modeling and laboratory experiments. For simplicity, both the modeling and experimental efforts focus on flexible blades with uniform rectangular cross-sections, characteristic of seagrasses. However, the model can easily be extended to account for more complex geometries and spatial variations in material properties. The numerical model is based on the well known Morison force formulation [see e.g. Denny et al., 1998] and allows for large blade deflections (Section 2.1). The experiments simultaneously measured the total hydrodynamic force exerted on the blade, imaged blade posture, and measured the local velocity field using particle image velocimetry. Two different blade materials, four different blade lengths, and eight different wave conditions were tested to yield a total of 64 experimental cases. These cases were chosen to correspond to environmentally-relevant dimensionless ranges. Despite the obvious simplification in modeling the hydrodynamic forces acting on the blade, the numerical model reproduces experimental force measurements and blade posture observations with reasonable fidelity, without the use of any fitting parameters.

Importantly, the numerical model also guides scaling analyses (Section 2.3) that generalize recent advances in our understanding of the reconfiguration of flexible vegetation in steady, unidirectional flows e.g. Alben et al., 2002; de Langre, 2008; Gosselin et al., 2010; Luhar and Nepf, 2011 and the wave-induced motion of flexible vegetation at the small-deflection limit (Mullarney and Henderson, 2010). For unidirectional flows, Luhar and Nepf (2011) showed that the reconfiguration of aquatic vegetation depends on two dimensionless parameters: the Cauchy number Ca, which represents the relative magnitude of the hydrodynamic forcing and the restoring effect of vegetation stiffness, and the buoyancy parameter B, which is the ratio of the restoring forces due to buoyancy and stiffness. For wave-induced oscillatory flows, a few additional parameters also play a role. These include the Keulegan–Carpenter number KC, which represents the ratio of the inertial forces to drag, as well as the ratio of the blade length to the wave orbital excursion, L. As will be shown later, the latter parameter sets the transition between the small deflection limit described by Mullarney and Henderson (2010) and a quasi-steady situation resembling unidirectional flows, thereby playing a key role in dictating blade behavior. To characterize the reduction in hydrodynamic forces (and therefore, wave energy dissipation) due to blade flexibility and motion, we propose the use of an effective blade length, defined as the length of a rigid upright blade that generates the same forces as the flexible blade.

2. Theory

2.1. Dynamic blade model

The model considers inextensible blades of width b, thickness d, length l, elastic modulus E, and density ρ_v moving in a two-dimensional plane. The blade is assumed to move without twisting, such that the frontal area exposed to the flow is always b per unit blade length. The coordinate system used is shown in Fig. 1, where s is the distance along the blade from

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