

EXPERIMENTS IN DIRECT ENERGY EXTRACTION THROUGH FLAPPING FOILS

Bradley J. Simpson, Franz S. Hover, Michael S. Triantafyllou
Department of Mechanical Engineering, Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

ABSTRACT

Work with fish has shown their ability to extract energy from unsteady flows and vortical structures. We demonstrate experimentally that foils performing a sinusoidal sway (heave) and yaw (pitch) motion, similar to a fish, with continuously controlled parameters such as yaw amplitude, Strouhal number, and phase angle between sway and yaw, can efficiently extract energy from unsteady flows. Aluminum NACA 0012 foils with aspect ratios of 4.1, 5.9, and 7.9 were tested at Reynolds numbers $\sim 13,800$. Overall efficiencies of up to $43 \pm 3\%$ are achieved with simple sinusoidal motions.

KEY WORDS: Wave energy; flapping foils; steady flow; swimming;

INTRODUCTION

As global warming effects are noticed and world energy consumption continues to rise, countries are placing larger emphasis on renewable energy sources. In addition to solar and wind power, the ocean holds significant promise as a sustainable energy provider. The abundance and consistency of ocean power offers a regular means of energy harvesting unmatched by wind or solar. An average power density of $2\text{--}3 \text{ kW/m}^2$ measured below the ocean surface and perpendicular to the wave front is the largest of all renewable energy sources (Falnes 2007) and is sufficient to meet the world's current energy demands.

There have been numerous methods designed for ocean energy extraction including ocean thermal energy (Vega 2002; Pelc 2002), wave energy (McCormick and Kraemer 2002; Muetze and Vining 2006; Falnes 2007), and current energy (Bryden et al. 2005; Ullman 2002). Our research is focused on wave and current energy systems, which have not been explored as thoroughly as ocean thermal systems. Wave energy conversion systems rely upon the periodic rise and fall of the ocean surface as the means to generate energy. Devices such as oscillating water columns, surging, pitching, and heaving devices have been developed to extract energy. Ocean current energy conversion systems rely on marine currents and tidal currents. The majority of these systems resemble windmills and use horizontal axis turbines to generate electricity from the flow; other systems use vertical axis turbines, oscillating vanes, and venturi constrictions (Bryden et al.

2005). In search of a better way to tap into this abundant source, we take our inspiration from the ability of marine animals to extract energy directly from the fluid flow around them. The oscillatory foil and body motions employed by fish for propulsion are of particular interest in the context of periodic wave forcing.

With flapping foils, marine animals extract ambient energy from a wide range of flows using both steady and unsteady flapping of their tails and fins. A number of researchers have been active in the area of fish propulsion including Kato (2000, 2003), Hover (2004), Schouveiler (2005), and Triantafyllou (2000); see Colgate and Lynch (2004) for a review. Flapping foil propulsion in air has been studied extensively and has led to research in wind energy extraction via flapping foil wings by McKinney and Delaurier (1981) and Jones et. al (1999); see Lindsey (2002) for a review. Recent work with both live and dead fish has shown their ability to harness ambient energy to the extent that passive thrust generation becomes feasible in the wake of an upstream object (Liao et al. 2003, Beal et al. 2006). The flow mechanism behind the oscillating foil is the vortex wake that appears in two forms: one indicative of drag and the other of thrust (Triantafyllou et al. 1991). The drag wake is a series of shed vortices that induce a velocity in the opposite direction of the free stream flow, resulting in a mean velocity profile deficit. For thrust generation, the foil oscillates to produce vortices that induce a velocity in the same direction as the free stream flow, resulting in a mean velocity wake larger than the free stream. Reversing this thrust generation process, it was observed that one could passively extract energy from flows.

We sought to experimentally determine the efficiency of direct energy extraction via a flapping foil. Of primary concern were the effects that the Strouhal number and the angle of attack profile had on the efficiency of energy extraction. Other parameters affecting the hydrodynamic performance were the phase angle between the sway and yaw motions, the aspect ratio of the foil, and the oscillation amplitude to chord length ratio. While the potential application of flapping foils in marine energy extraction systems is clear, we do not make direct comparisons with efficiencies and loading of conventional structures, such as horizontal-axis turbines, in this paper. This is because we have only tested a small subset of the possible parametric space, to establish a basic description of what is achievable with flapping foils for energy extraction.