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Wave energy conversion using fluidic flexible matrix composite power take-off pumps

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ABSTRACT

Fluidic flexible matrix composites (F2MCs) are composite tubes that consist of multiple layers of oriented, high performance fibers, such as carbon, precisely placed in a flexible matrix resin to form high-mechanical advantage actuators and variable stiffness materials. Unique to the F2MC tube is its ability to generate high pressures and volume change with a small external load as a result of the stiff reinforcement fiber orientation in the wall of the tube and the soft supporting elastomer. When a load is applied to the tubes, the volume of the F2MC tube is reduced and fluid is forced out of the tube by the reinforcing fibers. This is the first reported research on the design, fabrication, and characterization of F2MC tubes as power take-off (PTO) mechanisms for ocean wave energy conversion where the heaving motion of a floating body in waves provides the axial load that drives fluid through the pumps. An analytical model is developed to predict the performance of F2MC pumps in a variety of test conditions, and 1/50th scale F2MCs pumps are tested in a water basin. The scaled pumps are mechanically cycled between 0 Hz and 2 Hz at up to 17 percent strain replicating ocean waves of varying period and amplitude. Instantaneous input mechanical power and output fluid power values are calculated from force, velocity, pressure, and flow rate measurements, and the actuator efficiency is subsequently determined and compared with the prediction of the analytical model. At 1/50th scale, a maximum power conversion efficiency of 40 percent is obtained for a single pump and a peak output power of 0.21 W is recorded. At full scale, the predicted peak output power is 180 kW, suggesting that F2MC pumps are a promising class of fluid power take-off (PTO) mechanisms for ocean wave energy conversion, representing a substantial improvement over hydraulic cylinders.

1. Introduction

Ocean wave energy respresents one of the largest unused renewable energy resources available. Globally, there is an estimated 1 TW incident along global shorelines, and up to 10 TW incident along global continental shelf boundaries [1,2], as defined by the 200- to 500-m depth contour range, where the shelf transitions to deeper water. Among alternative sources of naturally renewable energy, wave energy offers the highest flux density, with an estimated global average intensity of 2–3 kW/m^2 per meter of wave front versus 0.1–0.3 kW/m^2 from solar radiation and 0.5 kW/m^2 from wind [1]. Although caused by surface winds, the local wind-driven wave field responds more slowly than the atmospheric boundary layer to changes in weather patterns, due to the much greater density of water vs. air. Moreover, once generated, ocean waves in deep water can travel vast distances as swell, with negligible loss of energy until encountering shelf waters. Thus wind energy flux across an entire ocean basin is ultimately experienced as wave energy flux along continental margins. As a result of these factors, wave energy is both more concentrated and more nearly continuous as compared with wind and solar energy [1]. Despite these advantages there are still challenges associated with wave energy conversion. At locations near shore, in shallower water depths interactions with the seafloor, such as refraction, shoaling, and breaking, reduce wave energy intensities [1–3]. Offshore wave energy intensities

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are typically higher (measured in tens of kilowatts per meter of wave front, as opposed to kilowatts per meter of wave front near shore), but the direction of the offshore waves is much more variable, requiring WEC devices that can efficiently absorb energy from all directions, or "weathervane" to continually face into the direction of greatest wave energy flux.

Modern offshore wave energy conversion (WEC) devices can be divided into three categories: attenuators, terminators, and point absorbers. Attenuators, are oriented with their principal axis perpendicular to the prevailing wave crests. An example attenuator is the *Pelamis* [4], which absorbs energy from waves passing along its principal axis by using hydraulic cylinders at the joints connecting its rigid, cylindrical hull segments, where a passing wave flexes these joints, causing the cylinders to pump hydraulic fluid. This pressurized fluid passes through a hydraulic motor-generator, and the generated electricity is transmitted to the shore via submarine power cables. A primary engineering challenge for attenuators is the design of mooring and riser power cable systems that enable the device to rapidly yaw (i.e. "weathervane") and remain head-on into the prevailing wave crests. As these devices become larger, their yaw response time becomes greater, which can reduce efficiencies in wave climates characterized by rapidly changing wave directions.

Terminators are oriented with their principal axis parallel to the wave front, with a notable example being a floating overtopping device known as the Wave Dragon [5], which consists of two floating barrier arms that form a large V that is open to the prevailing wave direction. Waves are funneled by these arms into a floating reservoir, that is filled as waves surge up a ramp and spill into the reservoir, leading to a reservoir level that is greater than the surrounding ocean level. The potential energy stored in the reservoir drives conventional low-head hydroelectric turbines to generate electricity as the water drains back to the ocean. These systems are mechanically simpler than attenuators, but experience much higher mooring forces, as the entire terminator structure is held in place against the prevailing wave crests.

Point absorbers, such as the OPT Powerbuoy [6], are heaving bodies whose principal dimension is much smaller than the prevailing wavelengths. They are designed to convert wave power from all directions and thus well suited for the omnidirectional offshore wave energy resource. The heaving motions of a surface absorber can be used to drive a hydraulic cylinder that in turn operates a motor-generator using a closed-circuit hydraulic system. Alternatively, a linear permanent-magnet generators (LPMG) can be driven by the buoy's heaving motion to directly generate electricity without a hydraulic intermediate stage. Within the point-absorber category, there is a distinction between single-body devices and two-body devices. Single-body devices use a single heaving absorber at the sea surface that is tethered to a seafloor anchor [3]. The heaving of the surface absorber drives either a hydraulic or LPMG power take-off (PTO) mechanism that is in-line with the mooring tether. Single-body point absorbers become less cost-effective in deeper waters, due to the longer mooring tether needed, and the larger absorber hull needed for additional buoyancy to support the added mooring tether weight. Single-body absorbers also must have PTO designs that can accommodate tidal changes in sea level.

Two-body point absorbers overcome the above-noted challenges by replacing the seafloor anchor with a suspended reaction plate, such that the entire absorber/tether-PTO/reaction-plate system can rise and fall with tidal changes in sea level, and the cost of the tether-PTO component remains constant, regardless of water depth.

The previous systems all act based on the translational motion associated with waves, in heaving, but there are other designs that operate using relative pitching motions, such as the Oyster, which is being developed in the UK [3]. Point absorbers can be mechanically simple much like overtopping devices, and typically leave a much smaller surface footprint. Additionally, these systems operate nearly independent of the wave direction, unlike attenuators or terminators, since they are only dependent on the wave amplitude and frequency. A common problem faced by conventional point absorbers is the difficulty in optimizing performance for wide ranges of wave amplitudes and frequencies, where it is only feasible to optimize efficiency at single design conditions.

Additional WEC devices have been designed and characterized in recent years. The Blow-Jet [7] is a converter that is similar in operation to Tapchan, but instead operates as a floating compression chamber that directs surface waves into converging section to amplify the fluid velocity and extract the kinetic energy through impulse turbines. Alternatively, new devices, such as magnetic gear mechanisms [8], have been proposed that does not rely on turbines for energy conversion. These may instead operate using the oscillating motion of a buoy, much like point absorbers, but instead use the translation of two magnetic gears through Lorentz forces. This has the advantage of being zero contact, having negligible friction, and alleviating part of the leaking due to corrosion. There is also current work being completed to fully characterize and better design existing systems, including point absorbers and attentuators [9,10]. Other creative approaches have investigated using the oscillations resulting from vortex induced vibration (VIV) to generate power. When a flexible bluff body such as cylinder is placed in the direction perpendicular to the flow of water, shedding alternating vortices on the top and bottom of the body result in alternating lift forces on top and bottom. This alternating lift force causes the bluff body to oscillate at a resonant frequency, which is referred to as a lock-in phenomenon. The VIVACE (Vortex Induced Vibration Aquatic Clean Energy) developed by Bernitsas and Raghavan at the University of Michigan converts ocean/river current to power using VIV and small scale experiments demonstrated that the system is promising [11,12]. The Underwater Compressed Air Energy Storage and the Vortex Induced Vibration Aquatic Clean Energy (UWCAES-VIVACE) is a hybrid system that uses charged compressed air accumulators as the bluff body to improve the overall efficiency of the VIVACE system [13]. Researchers have also investigated VIV with a linear generator to help increase the power conversion efficiency [14]. Wang et al. [15] numerically investigated a VIV system that uses a circular cylinder attached to two PZT beams for energy conversion, and voltages as high 8.41 V at a corresponding reduced velocity U_r of 5.6 were achieved [15]. More recently, Kim and Bernitsas showed that multiple cylinders in close proximity to one another can generate more electricity than the same number of cylinders each in isolation [16].

All WEC systems discussed above must cope with corrosion observed in the harsh ocean environment and complex mechanical systems that can fail. Therefore it is of interest to reduce the mechanical complexity of wave energy conversion technologies to allow for more robust systems that can operate in both near shore and open ocean environments, have a minimal environmental impact, and are easier to manufacture and implement. To provide such a system, the focus of this research is to look to nature for inspiration.

The jetting action of squid is a natural example of efficient pumping. Squid are the fastest aquatic invertebrates when jetting to escape predators, easily achieving velocities up to 25 body lengths per second and some up to 25 mph [17]. This done through a mantle (i.e. hydrostat) that quickly compresses an internal fluid, forcing fluid out through a funnel [18]. The squid mantle has a complex collagen fiber and muscular system with collagen tunic fibers arranged in a helical arrangement with respect to the longitudinal axis [17,19]. Squid propulsion is primarily done through circumferential muscles contacting around the mantel, forcing fluid out of the mantel [17]. However, jetting is also increased through elastic energy stored in the helically-wound IM-1 collagen fibers. It was found by Krieg and Mohseni that the jetting is optimal when the fibers are oriented at 31° with respect to the longitudinal axis [19]. The IM-1 angles have been measured between 28° and 32° in different species of squid [20].

Inspired by the helical fibers found in soft bodied hydrostats such as the squid mantle described above and shown in Fig. 1A, fluidic flexible matrix composites (F2MCs) are composite tubes that consist of multiple