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Low tidal current speed electricity generation for power at an aquaculture farm

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Abstract

Aquaculture farms are often located where tidal currents speeds are strong enough to ensure the currents supply fresh nutrients but not so strong that they harm the farm infrastructure. Traditional tidal turbines have cut-in speeds of 1 m/s and cannot generate electricity at current speeds below that threshold. Current energy converters that rely on vortex induced vibration (VIV) for movement can generate electricity at current speeds below 1 m/s. Here we discuss a project where researchers from the Pacific Northwest National Laboratory (PNNL) collaborate with researchers from the University of Michigan to investigate the feasibility of using a VIV current energy converter to generate electricity at an aquaculture farm. The VIV current energy converter uses flow induced oscillations of tandem cylinders and adaptive damping to harness the maximum horizontal marine hydrokinetic (MHK) energy by mimicking fish undulations. The current energy converter will be field tested and its power output measured over a range of current speeds. In addition to working with the University of Michigan, the PNNL researchers are collaborating with the Hog Island Oyster Company to assess their electricity usage and quantify the current energy resources at their Humboldt Bay facility. The electricity usage and current resource assessment at the aquaculture farm will be compared to the power produced by VIVACE to determine the feasibility of using VIVACE for power production at the farm.

Keywords: marine hydrokinetic energy; vortex induced vibration; tidal energy; powering aquaculture farms

1. Introduction

Aquaculture is a rapidly growing sector of the blue economy with the number of permits and acreage of farms increasing every year. As the aquaculture industry grows, its power needs will also increase. Aquaculture farms are often located where tidal currents deliver fresh nutrients but the currents are not being used to generate electricity. Tidal current energy converters could be used to generate electricity if the current speeds match speeds at which current energy converters can produce electricity. The ideal current speed range for kelp farms is between 0.5 and 1 m/s [1]. Some tidal current turbines can generate electricity at current speeds as low as 0.5 m/s, but they are typically only considered useful for electricity production at current speeds above 1 m/s [2]. Here we present a project to assess the potential of using a novel, low speed, current energy conversion device at an aquaculture farm. The project is composed

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of a test of a current energy conversion device and an environmental evaluation of an aquaculture farm to determine if the current speeds at the farm are high enough for the device to meet the farm power requirements.

2. MHK Energy harnessing Technology: The VIVACE Converter

2.1. Description

The current energy conversion device used in this work is called the VIVACE Converter. It consists of an array of oscillators, each comprised of a modified circular cylinder with turbulence stimulation, mounted on end-springs, and attached to a PTO (Power Take Off) system [3]. Fig. 1a shows an array of three oscillators in tandem, in a portable unit. In Fig. 1b the unit is being tested in the recircuiting channel of the MRELab (Marine Renewable Energy Laboratory) of the University of Michigan. In Fig. 1c it is dry tested for controls and power electronics at Vortex Hydro Power (VHP). VIVACE harnesses horizontal MHK energy from currents, tides, and rivers [4-7]. Compact formation is used by effectively implementing synergy between oscillators, thus, preventing shielding of the downstream cylinders. Maximum energy oscillation patterns are activated by mimicking fish-undulation shapes.

The flow past multiple oscillating bodies in compact formation is very complex as it involves interaction between stagnation points, boundary layers, separation points, shear layers, roll-up of vortices, von Kármán vortices, vortical wakes, and oscillating bodies. Numerous interaction phenomena occur resulting in various patterns with some generating more energy than the same number of cylinders in isolation, some enhancing the motion of the lead cylinder, and some causing suppression of downstream cylinder oscillations. The design space is multidimensional including spring stiffness, harnessing damping, spacing and staggering of cylinders, mass ratio, location and dimensions of turbulence stimulation, number if cylinders, flow speed, and more.

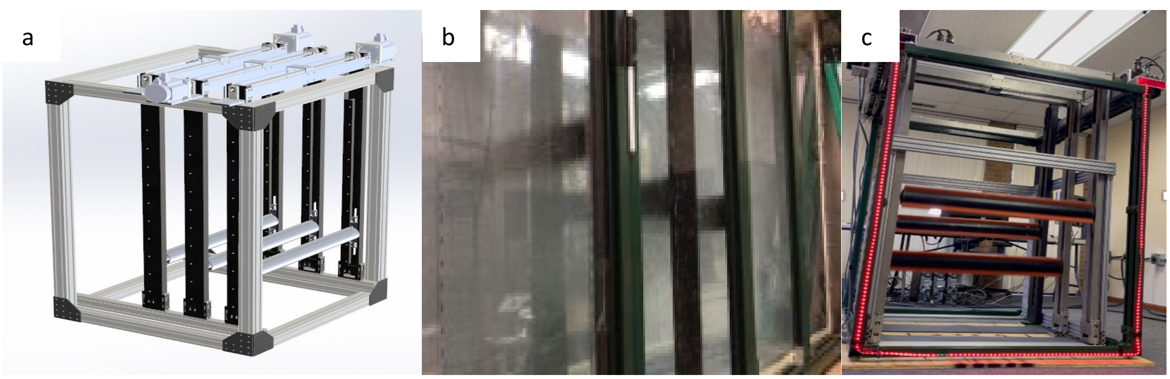

Fig. 1. (a) SolidWorks of portable 3-cylinder VIVACE; (b) Wet-testing with pattern mimicking fish undulation to maximize energy; (c) Dry testing of portable VIVACE.

2.2. Underlying Concept and Physical Phenomena

The overarching concept of the VIVACE technology is to harness MHK mimicking fish-school dynamics. The anticipated benefits are many, including environmental compatibility, energy harnessing starting at very low flow-speed, high scalability, and high energy density, which is the Achilles heel of all renewable energy technologies. The enabling breakthrough sought is to mimic interactive-dynamics of fish-flow without emulating the complex fish-school kinematics.

The following phenomena and concepts are utilized to realize the VIVACE technology:

- Fish propel efficiently using alternating lift and generating a well-organized vortical wake similar to a von Kármán wake, which cylinders – and bluff bodies in general – generate in a flow.
- When this alternating wake synchronizes with the oscillation of an elastic body, they resonate creating an efficient transverse, fluid-structure interaction referred to as VIV (Vortex Induced Vibration). This is a broad range nonlinear resonance due to variable added mass.

- Galloping is also a transverse lift phenomenon induced by geometric and/or flow asymmetry. Excitation is unidirectional and, thus, its periodicity is related only to the allowed travel span and is only indirectly related to the body's natural frequency.
- VIV and galloping coexist when galloping initiates before VIV desynchronization. As amplitude increases and body oscillation frequency changes, the VIV mechanism desynchronizes acting against the galloping alternating lift. In the latter case, a dip appears in the RAO.
- By properly designing the turbulence stimulation, the above phenomena can be triggered back-to-back resulting in an open-ended RAO (Response Amplitude Operator) as in Fig. 2a. It starts with linear resonance, proceeding with the initial and upper branches of VIV, advancing through coexistence with galloping, and continuing with fully developed galloping.
- The RAO initiates with linear resonance in water which can be designed to start at very slow flows when MHK energy may be small but most valuable.
- When multiple cylinders are involved the interaction phenomena are numerous and complex. We have identified 15 interactions resulting in lowering or increasing MHK energy harnessing.
- To enable harnessing energy from waves with VIVACE-W, the cylinder is placed horizontally, made neutrally buoyant, and use a controller to actively change its stiffness to match the oscillator's natural frequency to the incident wave's frequency [8].

High power oscillatory patterns were achieved without active motion control of multiple cylinders by implementing adaptive damping [10]. Instead of controlling the motion of each oscillator to achieve high output, the properties of the oscillator are adjusted to its response. The cylinders naturally precipitate into oscillatory fish-undulation patterns, which are the high energy output patterns (Fig. 2b).

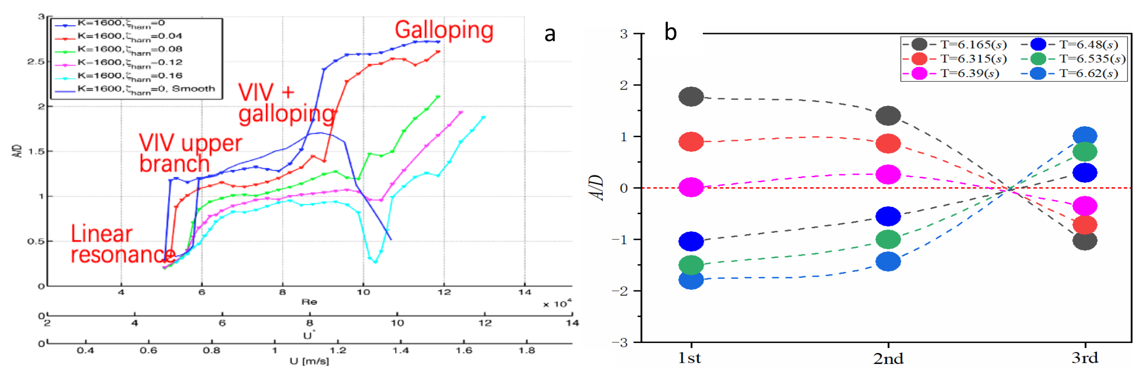

Fig. 2. (a) The Response Amplitude Operator (RAO) of VIVACE initiates as a typical linear oscillator; continues as a nonlinear oscillator with variable added mass; transitions to superposition of VIV and galloping; ending with open ended galloping; (b) Example of a fish-undulation oscillatory pattern. Positions of three tandem cylinders during half cycle of the first cylinder; $L/D = 2.01$, K=600N/m, $\zeta_{harness} = 0.24$, Re =114,000.

2.3 Performance and Benefits

- Efficiency reaches 88% of the Betz limit with 4 cylinders [7] over broad range of speeds (Fig. 2a).
- Power density is high due to compact formation using synergy of cylinders in FIO (Flow induced Oscillations), that is VIV, galloping and their coexistence.
- MHK energy generation over a wide range of flow rates, even as low as 0.5 m/s. Lowest flow speed achieved in lab was 0.19m/s.
- No impact on aquatic life as there are no turbine blades or rotors to create damage and cylinders move only about 20-40% faster than the flow [11].
- Quietly oscillating components due to low speed and friction.
- Turbulence stimulation allows operation even in turbulent flows.
- Portable power for specialty applications to support the Blue Economy and defense.

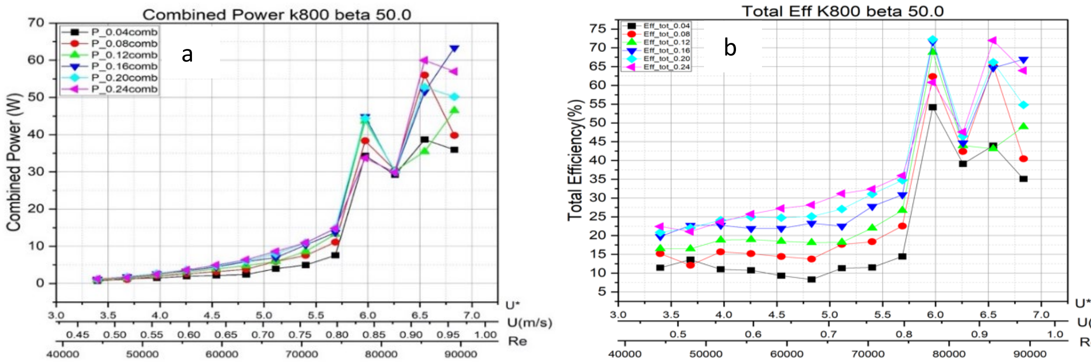

Fig. 3. (a) Three-cylinder VIVACE power: K=800N/m, $\zeta_{harness}\epsilon[0.04-0.24], \beta = 50.0$Ns^2/m^2; (b) Three-cylinder VIVACE efficiency: K=800N/m, $\zeta_{harness}\epsilon[0.04-0.24], \beta = 50.0$Ns^2/m^2.

3. VIVACE field testing at PNNL-Sequim

Field testing of VIVACE will take place at the PNNL-Sequim facility near the mouth of a Sequim Bay where tidal currents accelerate through a narrow channel. The current speeds vary spatially in the channel and have been measured as high as 2.82 m/s during peak tidal flows [12]. The PNNL coastal modeling group has modeled the current speeds through the mouth of Sequim Bay and calculated the power density (Fig. 4).

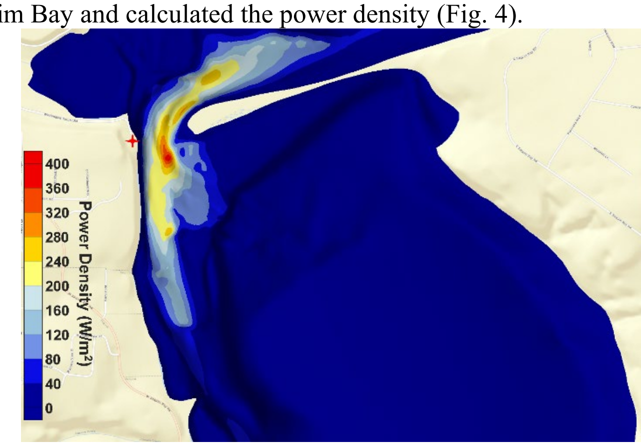

Fig. 4. Power density of the currents at the mouth of Sequim Bay as calculated by the PNNL Sequim Bay model. Red star marks the location of the PNNL-Sequim pier.

The test will take place on the PNNL-Sequim floating dock that is attached to the pier. VIVACE will be mounted with the moving cylinders submerged at a constant depth because the floating dock rises and falls with the tide.

4. Hog Island Oyster Company

The Hog Island Oyster Company is collaborating with the Pacific Northwest National Laboratory on a feasibility study of using tidal energy to generate electricity at their Humboldt Bay facility. The Humboldt Bay facility contains their hatchery and nursery where they cultivate oysters from the larval stage to single set spat. When the spat reach approximately 3 mm in size, they are transferred to the nursery and a floating upwelling system (FLUPSY) is used to circulate nutrients. The FLUPSY is located on a pier that stretches out into the bay and has significant power needs to operate a motorized paddle wheel and gantry crane.

5. Discussion

This project is an initial feasibility study of using a current energy conversion device to generate electricity at an aquaculture farm where the flow speeds are expected to be below 1 m/s. The study will measure the flow speeds at the farm and investigate the power needs of the farm. The current energy conversion device will be field tested at the PNNL-Sequim pier where the flow speeds are also expected to be below 1 m/s. The power generated at the PNNL-Sequim pier over a range of tidal velocities will be used to estimate how much power could be generated at the aquaculture farm. Future work could test an installation of the current energy conversion device at the farm.

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