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Performance prediction of horizontal hydrokinetic energy converter using multiple-cylinder synergy in flow induced motion

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HIGHLIGHTS

- Multiple cylinders in FIM work synergistically for hydrokinetic power harnessing.
- Peak power conversion efficiency was estimated at 88.6% of the Betz limit.
- Power-to-volume density reached 874.7 W/m^3 at flow speed of 1.45 m/s.
- VIVACE can efficiently harness energy from flows as slow as 0.8 m/s, with no upper limit.

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ABSTRACT

Horizontal hydrokinetic energy can be harnessed using Steady Lift Technology (SLT) like turbines or Alternating Lift Technology (ALT) like the VIVACE Converter. Tidal/current turbines with low mechanical losses typically achieve about 30% peak power efficiency, which is equivalent to 50.6% power efficiency over the Betz limit at flow speed nearly 3.0 m/s. The majority of flows worldwide are slower than 1.0–1.5 m/s. Turbines also require large in-flow spacing resulting in farms of low power-to-volume density. Alternating-lift overcomes these challenges. The purpose of this study is to show that the ALT Converter is a three-dimensional energy absorber that efficiently works in river/ocean currents as slow as 1.0–1.5 m/s a range of velocities presently inaccessible to watermills and turbines. This novel converter utilizes flow-induced motions (FIM), which are potentially destructive phenomena for structures, enhances them, and converts hydrokinetic energy to electricity. It was invented in the Marine Renewable Energy Lab (MRELab) and patented through the University of Michigan. MRELab has been studying the effect of passive turbulence control (PTC) to enhance FIMs and to expand their synchronization range for energy harnessing. This study shows that multiple cylinders in proximity can synergistically work and harness more energy than the same number of a single cylinder in isolation. Estimation based on experiments, shows that a 4 PTC-cylinder Converter can achieve 88.6% peak efficiency of the Betz limit at flow speed slower than 1.0 m/s and power-to-volume density of 875 W/m^3 at 1.45 m/s. Thus, the Converter can efficiently harness energy from rivers and ocean current as slow as 0.8–1.5 m/s, with no upper limit in flow velocity.

1. Introduction

River or ocean tidal currents have an enormous potential for electric power generation. Ocean currents and river flows are highly predictable and seasonally consistent during a year compared to wind or waves. Various scales of tidal current converters have been successfully developed, installed, and tested [1,2]. The overall power efficiencies are approximately 30% for typical tidal turbines with low mechanical losses and 40–45% for few well-designed systems [3,4]. Those numbers are equivalent to 50.6% and 67.5–75.9% for the power efficiency over the Betz limit, respectively. Most of the marine turbines generate the rated power at a nominal design flow speed faster than 2.0 m/s while the vast

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Nomenclature

A	amplitude (m)
$A_{\max}$	the largest amplitude among all multiple cylinders (m)
B	center-to-center distance between cylinders (m)
C_a	inviscid added mass coefficient
$c_{harness}$	harness damping coefficient (Ns/m)
c_{sys}	system damping coefficient (Ns/m)
D	diameter of the cylinder (m)
$E_{VIVACE\_N} = \sum_{i=1}^{N}\left(\frac{1}{2}KA^2 + \int_0^T c_{sys}\dot{y}^2 dt\right)_i$	converted energy by N-number of the cylinders (J)
f_{osc}	oscillation frequency of the cylinder (Hz)
$f_{n,w} = \frac{1}{2\pi}\sqrt{\frac{K}{m_{osc}+m_a}}$	natural frequency in water (Hz)
K	spring stiffness (N/m)
k	average particle diameter of the roughness strip (μm)
L	length of the cylinder (m)
m_{osc}	oscillating mass including 1/3 of the spring mass (kg)
m_a	ideal added mass (kg)
m_d	fluid mass displaced by cylinder (kg)
$m^* = m_{osc}/m_d$	mass ratio
N	number of the cylinders
p	thickness of backup paper and double-sided tape of the roughness strip (μm)
P_{VIVACE_N}	converted mechanical power by N-number of the cylinders (W)
$P_{Harness\_N}$	harness power by N-number of the cylinders (W)
$P_{fluid} = \frac{1}{2}\rho U^3(2A_{\max} + D)L$	power in fluid in the area swept by the cylinders (W)
$PVD = \frac{(\frac{P_{VIVACE\_4}}{4})\times 6}{3B\times 6D\times L}$	power-to-volume density (W/m^3)
$S_{synergy} = \frac{E_{VIVACE\_N}}{N\times E_{VIVACE\_1}}$	synergy scale
T	period of oscillation (s)
t	time (s)
U	flow speed (m/s)
$U^* = \frac{U}{f_{n,w}D}$	reduced velocity
$y(t)$	displacement of the cylinder (m)
$\dot{y}(t)$	velocity of the cylinder (m)
ζ_{sys}	system damping ratio
η_{mech}	mechanical power efficiency (%)
$\eta_{convert}$	power conversion efficiency (%)
$\eta_{harness}$	power harness efficiency (%)
ρ	density of a fluid (kg/m^3)

majority of currents are slower than 1.5 m/s and typical rivers are slower than 1.0 m/s [3–5]. Thus, technological breakthroughs are needed to be able to harness the power of typical ocean and river currents and convert it to electrical power. In this paper, a multi-cylinder VIVACE Converter is introduced, which can generate power at flow speeds slower than 0.8–1.5 m/s with high power conversion efficiency and high power-to-volume density. Presently, the Technology Readiness Level (TRL) of this Converter is 7 out of 9. TRL is based on the classification by the United States Department of Energy, and 7 corresponds to a prototype near or at planned operational system. A 4 kW-four cylinder prototype shown in Fig. 1 is under production and will be deployed in the St. Clair River, Port Huron, Michigan U.S.A. in the Spring of 2016. It is a converter of horizontal marine hydrokinetic (MHK) energy to electricity invented in the Marine Renewable Energy Lab (MRELab), first introduced in 2006 [6], and patented by the University of Michigan in 2009 [7,8]. Unlike previous efforts to suppress the occurrence of Flow Induced Motions (FIM), which is a potentially destructive phenomenon for structures subjected to a fluid flow, the Converter enhances and utilizes FIMs to harness power from river and ocean currents.

Vortex-Induced Vibration (VIV) is one of the well-known FIMs, which is induced on flexible bluff bodies such as circular cylinders exposed to a fluid flow perpendicular to the cylinder axis. Boundary layers separate from the surface on either side of the body, giving rise to a broad wake behind it where the free shear layers roll and form vortices. These vortices are alternatingly shed from either side of the body, altering the pressure distribution causing periodic forces to act on the cylinder leading to VIV. It is a lock-in or synchronization phenomenon [9–11]. Galloping is another well-known form of FIM discussed later in this section. Typically, and in this paper, the various FIM flow regimes are plotted vs. reduced velocity U^*, which is defined as

$$U^* = \frac{U}{f_{n,w}D} \tag{1}$$

where

$$f_{n,w} = \frac{1}{2\pi}\sqrt{\frac{K}{m_{osc}+m_a}} \tag{2}$$

K is spring stiffness, m_{osc} is oscillating mass including 1/3 of the spring mass, and m_a is the added mass. VIV occurs over a range of U^*, which varies widely depending on the mass ratio m^* defined by the oscillating mass over the fluid mass displaced by the cylinder. For a mass ratio around $m^* \approx 1$, that is for a neutrally buoyant body, this range is about $5 < U^* < 10$ [12].

Calculation of the added mass appearing in the definition of the natural frequency in water ($f_{n,w}$) in Eq. (2) is performed in two different ways and is still being debated. Both methods assume that the response in VIV can be modeled as sinusoidal by a single degree of freedom oscillator as

$$m_{osc}\ddot{y} + c_{total}\dot{y} + Ky = F_{Fluid,y} \tag{3}$$

with $y(t) = y_{osc}\sin(\omega_{osc}t)$ and $F_{Fluid,y}(t) = F_{osc}\sin(\omega_{osc}t + \phi)$.

The first approach separates the added mass from the right hand side assuming that it can be approximated by the inviscid added mass for a cylinder

$$m_a = C_a\rho\frac{\pi D^2}{4}L = C_a m_d = m_d \tag{4}$$

The inviscid added mass coefficient is $C_a = 1$. FIM results are presented vs. U^* defined by Eq. (1) with the added mass given by Eq. (4). In this case VIV is interpreted as a lock-in phenomenon where the vortex shedding frequency is locked on to the frequency of oscillation f_{osc} [11].

The second approach does not to separate the added mass from the hydrodynamic force on the right hand side of Eq. (4). In that case the added mass coefficient is calculated as the term in-phase with the motion acceleration $\ddot{y}$, which can be calculated by Eq. (5)