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

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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 3.0m/s. The majority of flows worldwide are slower than 1.0m/s-1.5m/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 1.0m/s-1.5m/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 cylinders 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 1.0m/s and power-to-volume density of 875W/m^3 at 1.45m/s. Thus, the Converter can efficiently harness energy from rivers and ocean current as slow as 0.8m/s - 1.5m/s, with no upper limit in flow velocity.

Keywords: Renewable energy, horizontal hydrokinetic energy converter, flow induced motion, energy conversion efficiency, power to volume density, distributed roughness, alternating lift-technology.

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

1 tidal turbines with low mechanical losses and 40%-45% for few well-designed systems [3, 4].
2 Those numbers are equivalent to 50.6% and 67.5%-75.9% for the power efficiency over the Betz
3 limit, respectively. Most of the marine turbines generate the rated power at a nominal design
4 flow speed faster than 2.0m/s while the vast majority of currents are slower than 1.5m/s and
5 typical rivers are slower than 1.0m/s [3, 4, 5]. Thus, technological breakthroughs are needed to
6 be able to harness the power of typical ocean and river currents and convert it to electrical power.
7 In this paper, a multi-cylinder VIVACE Converter is introduced, which can generate power at
8 flow speeds slower than 0.8m/s-1.5m/s with high power conversion efficiency and high power-
9 to-volume density. Presently, the Technology Readiness Level (TRL) of this Converter is 7 out
10 of 9. TRL is based on the classification by the United States Department of Energy, and 7
11 corresponds to a prototype near or at planned operational system. A 4kW-four cylinder prototype
12 shown in Fig. 1 is under production and will be deployed in the St. Clair River, Port Huron,
13 Michigan U.S.A. in the Spring of 2016. It is a converter of horizontal marine hydrokinetic
14 (MHK) energy to electricity invented in the Marine Renewable Energy Lab (MRELab) and first
15 introduced in 2006 [6] and patented by the University of Michigan in 2009 [7, 8]. Unlike
16 previous efforts to suppress the occurrence of Flow Induced Motions (FIM), which is a
17 potentially destructive phenomenon for structures subjected to a fluid flow, the Converter
18 enhances and utilizes FIMs to harness power from river and ocean currents.

Figure 1. Artist's rendition of a 4kW-four cylinder VIVACE Converter (courtesy of Vortex Hydro Energy)

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 alternately 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

$$U^* = \frac{U}{f_{n,w} D} \quad (1)$$

where

$$f_{n,w} = 2\pi \sqrt{\frac{K}{m_{osc} + m_a}} \quad (2)$$

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

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

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

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

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)

$$C_a = \frac{2U_m T}{\pi^3 D} \int_0^{2\pi} \frac{F}{\rho D U_m^2} \sin\theta d\theta \quad (5)$$

where $U_m = y_{osc} \omega_{osc}$ is the magnitude of the oscillatory velocity of the cylinder. The outcome of this formulation is that over the VIV range of synchronization the calculated natural frequency in water ($f_{n,w}$) in Eq. (2) comes out to be equal to the frequency of oscillation. As a result, VIV can be interpreted as a resonance phenomenon with variable added mass, and consequently variable $f_{n,w}$, over the entire range of synchronization between vortex shedding and the frequency of oscillation f_{osc} [13].

Using the first vs. the second approach, affects the presentation of results only, as the dimensional data can be retrieved from either presentation. It is the authors' opinion that this controversy is unnecessary as both are simple modeling methods that cannot account for the range of synchronization or the self-limiting nature of the amplitude of VIV oscillation. Both methods just model the response of the cylinder in FIM for a specific flow velocity and a given experiment. On the other hand, both approaches are useful in post-processing data and understanding this complex phenomenon better. For better understanding of the complexity of the added mass expression in forces and moments on a small body moving in a 3-D unsteady flow, the reader is referred to the detailed analysis by Foulhoux and Bernitsas [14]. The dependence of the inertia terms on absolute and/or relative velocity as well as the form of convective terms is explained thoroughly putting into perspective the simplicity of the inertia term used in Morison's equation.

The second FIM used in the Converter is galloping. Galloping is an aero/hydro-elastic instability, which is characterized by lower frequencies and higher amplitudes than VIV and is perpendicular to the flow. It is more vigorous and destructive than VIV, yet not as complex a phenomenon as VIV. Galloping does not depend on vortex formation, occurs above a critical flow speed, and has much bigger amplitude of oscillation. Elastic bodies with circular cross section in a flow usually experience VIV, while galloping occurs on a body with non-circular cross section [15]. Flow around multiple cylinders is much more complex than that around a single cylinder because of mutual interactions between shear layers, vortex shedding, vortex

structures, and wakes [16, 17]. All these add to strong nonlinear interaction between cylinders. The interference effects strongly depend on the number and arrangement of the cylinders, natural frequency of each cylinder-oscillator ($f_{n,w}$), mass ratio, damping, and Reynolds number (Re) range, and reduced velocity U^* defined by equation (1).

In order to enhance FIMs on the circular cylinder, MRELab has developed passive turbulence control using roughness strips selectively placed on the cylinder surface. The Converter with the PTC was extensively studied in the MRELab experimentally [18-23] and numerically as well [24-27]. The previous studies in the MRELab show that by introducing the PTC galloping initiated on the circular cylinders at the end of VIV and the oscillation amplitude dramatically increased as the flow speed reached the limit of the water channel.

The simplest form of the VIVACE Converter is a single smooth cylinder suspended by two end-springs with a Power-Take-Off system. Lee et al. [28] reported that the Converter with single-cylinder ($D=8.9\text{cm}$, $L=91.4\text{cm}$) successfully generated hydrokinetic power from a current as slow as 0.4m/s and a maximum power of 15.85W at flow speed of 1.11m/s . Chang [29] was able to harness 49.35W with a power-to-volume density of 341W/m^3 , at flow speed of 1.45 m/s using the identical single cylinder with the PTC. The conversion efficiency over the Betz limit was 40.25% at the same flow speed, which was calculated based on the power in a fluid (denominator) in the projected area of the cylinder, $D \cdot L$ where D , and L are the diameter, and length of the cylinder, respectively.

The current goal of the MRELab is to improve conversion efficiency and power-to-volume density by utilizing synergy among multiple cylinders with PTC. The experimental study [22] and numerical studies [26, 27] on FIMs of multiple cylinders, which were based on the identical test-setup with this study, well demonstrated the phenomena of VIV, transition between VIV and galloping, and galloping. Further, vortex shedding patterns and wake interactions were studied. It should be emphasized that the present study, apart from revealing the hydro dynamics of FIMs of multiple cylinders, focuses on proving the synergy between multiple cylinders in the energy conversion process to generate higher efficiency and power-to-volume density. This synergy

enables the VIVACE Converter to operate as a real three-dimensional energy absorber. The cylinders operate like fish in a school taking advantage of interaction hydrodynamics.

In this work, all tests were conducted in the LTFSW Channel with two, three, and four cylinders, with the horizontal distance between the centers of cylinders varying from $2.5D$ to $5.0D$. Mechanical energy converted from hydrokinetic to mechanical in the Converter is calculated and presented as a function of the flow speed, reduced velocity, and Reynolds number. Additionally, the power conversion efficiency and power-to-volume density for the four-cylinder Converter are estimated based on the data measured by the single-cylinder Converter [29, 30] and measured synergy scale, which is defined by the total converted energy by four cylinders over that of a single cylinder.

2. EXPERIMENTAL SET-UP

2.1. Low Turbulence Free Surface Water Channel.

All tests were conducted in the LTFSW Channel, in MRELab, which re-circulates about 30,000 liters of fresh water at speed up to 2.0m/s by an impeller powered by a 20HP induction motor. The turbulence intensity normalized by the free-stream velocity was reported at 0.095% [31]. The test section is 2.44m long, 1m wide, and 0.8m deep and made by transparent plexi-glass so as to facilitate visualization of the flow past the cylinders. For this study, the maximum flow speed was limited to be below 1.4m/s because the cylinders started to hit the stoppers at the flow speed of 1.34m/s. The safety-stoppers were installed to protect the bottom plexi-glass of the test section from breaking by the cylinder impact. A schematic of the LTFSW Channel is shown in Fig. 2.

Figure 2. Schematic of the LTFSW Channel with test modules

2.2. Oscillators

Figure 3 shows a schematic of the single-cylinder VIVACE Converter. A rigid circular cylinder of diameter D and length L is suspended by two linear end-springs, each with stiffness $K/2$; and damping c_{sys} of the transmission mechanism and the PTO. The cylinder is free to oscillate only transversely to the flow. The four modules of the single-cylinder Converter also shown in Fig. 2 can slide on a rail system to adjust the longitudinal distance between cylinders in tandem configuration. In this study, center-to-center distance between any consecutive cylinders changes from $2.5D$ to $5.0D$. Specific design particulars of the four single-cylinder Converter modules are listed in Table 1. All spring stiffness and structural damping were measured by a series of free decay tests in air. For all tests, physical linear springs are used rather than the Vck system used in systematic testing for generation of power envelopes of the single-cylinder Converter. A new Vck system for the multi-cylinder Converter has been developed [32] and optimal power envelope of the multi-cylinder Converter will be presented in the near future. In this study, the power conversion efficiency and power-to-volume density for the multi-cylinder Converter is estimated based on the data measured by the single-cylinder Converter and synergy scale for multiple cylinders in synergistic FIM.

Table 1. Particulars of the four single-cylinder VIVACE Converter modules

Parameters	Symbol	1st Device	2nd Device	3rd Device	4th Device
Diameter (m)	D	0.089	0.089	0.089	0.089
Length (m)	L	0.914	0.914	0.914	0.914
Oscillating mass (kg)	m_{osc}	9.53	9.59	9.51	9.58
Spring stiffness (N/m)	K	744.29	757.41	737.24	747.39
System damping ratio	ζ_{sys}	0.0206	0.0198	0.0172	0.0168
System damping (Ns/m)	c_{sys}	3.464	3.382	2.882	2.834
Natural freq. in water	$f_{n,w}$	1.114	1.121	1.109	1.114
Fluid mass displaced by cylinder (kg)	m_d	5.671	5.671	5.671	5.671
Mass ratio (m/m_d)	m^*	1.681	1.690	1.677	1.689
Added mass (kg)	m_a	5.671	5.671	5.671	5.671

Figure 3. Schematic of a single-cylinder Converter (left); Four-modules of single-cylinder Converter in the LTFSW Channel (right)

2.3. Passive Turbulence Control

Passive turbulence control has been studied extensively in the MRELab to alter the FIM [18-29] of cylinders on end-springs. The PTC-to-FIM map for a single circular cylinder has been developed [33]. The PTC method developed in the MRELab is a simple and very effective turbulence simulation method using roughness strips selectively placed on the cylinder surface. The strip whose thickness is about equal to the thickness of the boundary layer affects profoundly the characteristics of the boundary layer and shear layer. By increasing turbulence intensity, the PTC makes the laminar boundary and shear layers transition to turbulent at relatively low Re. At the same time, the PTC geometrically produces asymmetry on the circular cylinder with respect to the variable angle of incident flow and fixes the separation of the boundary layer at the front edge of the strip. These two effects initiate high amplitude galloping on all cylinders at very low reduced velocity ($U^* \approx 11$) regardless of the number of cylinders in the tandem configuration and center-to-center spacings between two successive cylinders. At $U^* \approx 11$, smooth cylinders (without PTC) would reach the desynchronization range of VIV resulting in rapidly decreasing oscillatory amplitudes [22, 26].

Previous experimental studies on the PTC-to-FIM map showed that galloping occurs when P60 sand strips are attached anywhere between 2° and 62° [19] from the forward stagnation point. A follow-up experimental study by Park et al. showed the map robustness [21]. This wide range of the coverage is one of the strengths of PTC because it works as expected even if some design misalignment or flow direction change occurs in ocean or river operation.

In this work, P60 sand strips in 12.7mm wide are attached symmetrically and parallel to the cylinder axis along the entire length of the cylinder as shown Fig. 4. Each sand strip covers 16° degrees on each side on the cylinder symmetrically with respect to the flow. Strip starts at 30° and ends at 46° on the cylinder surface measured from the forward stagnation point. The details of the roughness strip are presented in Table 2.

Figure 4. Roughness strip configuration (reproduced from H.R. Park, 2012)

Table 2. Details of roughness strip

ISO/FEPA Grit designation	Average particle diameter (k)	Thickness of backup paper and double- sided tape (p)
P60	$269\mu m$	$578\mu m$
k/D	$(k+p)/D$	Width
$302 \cdot 10^{-5}$	$951 \cdot 10^{-5}$	12.7mm(16° for $D=8.9\text{cm}$)

2.4. Instrumentation and Data Collection

The oscillatory displacement response of the cylinder is measured by a cable extension position transducer (potentiometer) and is recorded. The sampling rate of the data acquisition system is 100Hz. For each speed of the flow, after steady state has been reached, 60 seconds of the displacement data are measured. The oscillation amplitude and the corresponding standard deviation are calculated using the RMS of the 60 largest (positive or negative) amplitude values. The oscillation frequency f_{osc} is calculated by a Fast Fourier Transform over the 60 second recorded period.

2.5. Energy Conversion and Synergy Scale

In previous studies on a single-cylinder VIVACE Converter, the generated power was measured by introducing additional harness damping into the Converter system using the virtual damper-spring (Vck) system [28-30]. The Vck system replaced the real damper and real springs of the Converter system by a servo-motor and electric control system. Further details of the Vck system can be found in the paper by Lee et al. [30] and Sun et al. [32]. MRELab has conducted systematic tests with a single-cylinder Converter by changing the spring stiffness K and damping ratio ζ using the Vck system over the entire range of flow speeds. This process generated the optimal power envelope as a function of the flow speed, reduced velocity, and Re [28, 29]. Lee et al. [28] reported that the single-cylinder ($D=8.9\text{cm}$, $L=91.4\text{cm}$) Converter successfully generated hydrokinetic power from a current as slow as 0.4m/s and a maximum power of 15.85W at flow speed of 1.11m/s. Moreover, by utilizing the PTC, Chang [29] was able to

initiate galloping right after VIV and harness 49.35W at the flow speed of 1.45 m/s. This achieved power-to-volume density of 341W/m³, which is based on the fluid power in an assumed configuration of staggered cylinders with in-flow spacing of 8.0D and transverse spacing of 5.0D.

The purpose of this study is to evaluate the synergy of multiple cylinders on the energy conversion and power-to-volume density and show that the VIVACE Converter is a unique energy converter operating like a three-dimensional energy absorber. Members of the school of cylinders take advantage of interaction between cylinders like fish in a school [34]. In order to evaluate the FIM synergy of multiple cylinders in tandem on the energy conversion, the converted energy, E_{VIVACE_N} , which is converted from the hydrokinetic energy in the flow to the mechanical energy in the Converter system, is introduced and defined as

$$E_{VIVACE_N} = \sum_{i=1}^N \left(\frac{1}{2} K A^2 + \int_0^T c_{sys} \dot{y}^2 dt \right)_i \quad (6)$$

where A and N are the amplitude of the oscillation and number of cylinders, respectively. On the right hand side of Eq. (6), the first term accounts for the potential energy alternating with kinetic and stored in the oscillators and the second term is the work done by the system damping-force per cycle. For the multi-cylinder Converter with the PTC, years of testing are required to produce the optimal power curve at various flow speeds due to the high number of design parameters. Even with the Vck system, which eliminates down time between parameter changing, several years of testing are required. Such tests are being conducted in the MRELab and results are published gradually. For this study, additional harness damping is not introduced into the system and only quantitative comparison on the energy conversion is made in terms of total converted mechanical energy from the flow to the multi-cylinder Converter.

Assuming that the oscillation of a cylinder in FIM is sinusoidal, Eq. (6) can be rewritten as

$$\begin{aligned} E_{VIVACE_N}(J) &= \sum_{i=1}^N \left(\frac{1}{2} K A^2 + \int_0^T c_{sys} (2\pi f_{osc} A \cos(2\pi f_{osc} t))^2 dt \right)_i \\ &= \sum_{i=1}^N \left(\frac{1}{2} K A^2 + 2\pi^2 c_{sys} f_{osc}^2 A^2 \right)_i \end{aligned} \quad (7)$$

where f_{osc} is the oscillation frequency.

The total converted energy, E_{VIVACE_N} , is the sum of the energy captured by all cylinders. The synergy scale, $S_{synergy}$, is defined as

$$S_{synergy} = \frac{E_{VIVACE_N}}{N \times E_{VIVACE_1}} \quad (8)$$

where E_{VIVACE_1} is the converted energy by a single cylinder in isolation in FIM at the same speed.

3. RESULTS

In this study, the number of the cylinders and the center-to-center distance are the parameters being varied. For all tests, the PTCs were attached symmetrically on both sides of the cylinder surface at 30°-46°.

3.1. Converted Energy

The oscillatory amplitude and frequency were measured at various flow speeds from 0.51m/s to 1.30m/s and the energy converted by 1, 2, 3, and 4 cylinders in tandem array with the center-to-center distance of $2.5D$, $3.0D$, $3.5D$, $4.0D$, and $5.0D$ is calculated by Eq. (7). The calculated energy converted by multiple cylinder arrays is shown in Fig. 5. The error bars show the standard deviation of the converted energy, which is typically less than 1%. The maximum error bar occurs in the four-cylinder array reaching 2%~10% around $U^*=11$, where transition from VIV to the galloping occurs. The experiments had to be stopped at flow speed of about 1.30m/s because the amplitude of all cylinders reached the physical limits of the Channel hitting the safety stops and the free surface drop. It should be emphasized that galloping is an aero/hydro-elastic instability and the oscillation amplitude keeps increasing with increasing velocity until the structure fails if there is no physical limit [15].

Figure 5. Converted energy by multiple PTC-cylinders in FIM

As expected, the more cylinders are included in the array the more hydrokinetic energy is converted to mechanical in the oscillators. A consistent and very useful result in design of multi-cylinder Converters is that the center-to-center distance doesn't affect much the energy conversion especially in the region of $U < 1.08 \text{ m/s}$. For spacing of $3.0D$, the converted energy in galloping is less than that of other spacings. The maximum energy of 81J~88J was captured from the fluid energy by the four cylinders at the flow speed of 1.30m/s.

3.2. Synergy Scale

The synergy scale, as defined by Eq. (8), is a factor showing the synergy of multiple cylinders in harnessing energy. The total energy converted by multiple cylinders is normalized by the number of cylinders and the converted energy by a single PTC-cylinder in isolation. Figure 6 shows the important conclusion that the values of the synergy scale for 2, 3, and 4 cylinders are greater than 1.0 in the flow velocity range of $0.79 \text{ m/s} < U < 1.12 \text{ m/s}$. At the flow-speed of 1.08m/s, for 3 and 4 cylinders, the synergy scale value is 1.95 and 1.91, respectively. This means that the average of the energy converted by each cylinder in the tandem array is almost two times

more than that of the same cylinder in isolation. Even for the four cylinders in the smallest spacing of $2.5D$, the value reaches up to 1.65. Moreover, Kim [35] reported that for two cylinders in tandem array with the center-to-center distance of $1.43D$, the converted energy is higher than that of the two cylinders in larger spacings at most of the flow speeds. These results prove that the synergy of multiple cylinders in proximity on harnessing energy can be greater than the sum of the energies converted by each cylinder acting in isolation. In the range of $1.30\text{m/s} < U < 1.45\text{m/s}$, the synergy scales for the flow speed are projected based on the average of the last three values in order to estimate converted power for comparison in Section 4.1. The synergy scales become smaller than 1.0 for $U > 1.12\text{m/s}$ for all numbers of cylinders. For the two cylinders, the synergy scale is almost to 0.9 and even for the four cylinders, it remains around 0.8 regardless of the center-to-center distances between cylinders. This means that even with small spacing, each cylinder in tandem array still can harness energy efficiently. All these results indicate that the synergy of multiple cylinders can make the VIVACE Converter become a real unique three-dimensional energy absorber and, thus, overcome at least partially the greatest challenge all forms of renewable energy technology face: low power density.

Figure 6. Synergy scale of multiple cylinders in tandem array

4. DISCUSSION

4.1. Estimation of Converted Power and Harnessed Power

Chang [29] measured the harnessed power captured from the flow to the VIVACE system by changing the spring stiffness and damping using the Vck system at flow speed of $0.4\text{m/s} < U < 1.45\text{m/s}$ and produced the optimal harnessed power curve for the single cylinder with the PTC.

The converted mechanical power, P_{VIVACE} , is defined as

$$P_{VIVACE_N}(W) = \sum_{i=1}^N \left(\frac{1}{T} \int_0^T (c_{harness} + c_{sys}) \dot{y}^2 dt \right) = \sum_{i=1}^N (P_{harness} + P_{diss})_i \quad (9)$$

where T is the period of oscillation; $c_{harness}$ is the harness damping coefficient introduced by the Vck system which simulates the generator; c_{sys} is the system damping coefficient, which dissipates power; and $\dot{y}$ is the velocity of the cylinder transversely to the flow. Chang [29] showed that the value of the spring stiffness and harness damping at each flow speed is very important to maximize the harnessed power. In this study, four modules of the identical single cylinder unit used in Chang's tests were built and tested. For multiple cylinder Converters, the number of combinations of the spring stiffness K_i , harnessing damping $c_{harness}$, and spacing can be very high. In order to produce the optimal power curve for the multi-cylinder Converter, the MRELab has developed the new Vck system, which nearly eliminates time lag using a dedicated Arduino board [32]. Two Vck systems are operational and two more will be ready soon. In this paper, the converted mechanical power by multiple cylinders is estimated as

$$P_{VIVACE_N}(W) = P_{VIVACE_1} \times S_{synergy} \times N \quad (10)$$

where P_{VIVACE_1} is the optimal mechanical power of the single isolated PTC-cylinder as measured by Chang [29]. The average mechanical power efficiency, η_{mech} , of the four modules is 84.29% which is calculated by the dissipated energy due to the structural damping over the total converted energy. The harnessed power by the multiple-cylinder Converter is calculated as

$$P_{Harness_N}(W) = \eta_{mech} \times P_{VIVACE_N} \quad (11)$$

The resulting converted power and harnessed power by the multiple-cylinder arrays are plotted in Fig. 7. The converted mechanical power gradually increases as flow speed rises until 1.08m/s and suddenly drops in the flow-speed range $1.08\text{m/s} < U < 1.16\text{m/s}$, where the transition occurs from VIV to galloping. Once galloping is initiated the converted power curve steeply surges with

a small increase in the flow speed. The effect of the center-to-center distance is clearly shown in the flow-speed range of $1.08\text{m/s} < U < 1.16\text{m/s}$, where the converted mechanical power rises with increasing in the spacing, while it is not much affected by the spacing after the galloping initiates except for the spacing of $3.0D$. For the spacing of $3.0D$, the converted mechanical power by the multiple cylinders is lower than that for the other spacings. For the four-cylinder array, the estimation shows that the converted mechanical power reaches 135.0W at $U=1.08\text{m/s}$ and it is 194.1W at $U=1.45\text{m/s}$. For the single cylinder, the converted power measured by Chang [29] at $U=1.45\text{m/s}$ was 56.4W . The harnessed power will be 15.71% less than the converted mechanical powers due to the power dissipation by the structural damping. The converted mechanical power and harnessed power will keep increasing if there is no physical limitation as the flow speed rises because all of the cylinders are in galloping, which is an instability phenomenon with high oscillatory amplitudes.

Figure 7. Estimation of converted power and harnessed power

4.2. Estimation of Power Conversion Efficiency

The power in a fluid is calculated based on the area swept by the cylinders.

$$P_{fluid}(W) = \frac{1}{2} \rho U^3 (2A_{max} + D)L \quad (12)$$

- 1 where A_{max} is the largest amplitude among all multiple cylinders. The Betz limit is the theoretical
2 maximum power, which can be extracted from an open flow, and its value is 59.26% (16/27).
3 Based on the Betz limit, the power conversion efficiency, $\eta_{convert}$, and power harness efficiency,
4 $\eta_{harness}$, can be calculated as

$$\eta_{convert_N}(\%) = \frac{P_{VIVACE_N}}{P_{fluid} \times \text{Betz limit}} \times 100 \quad (13)$$

$$\eta_{harness_N}(\%) = \frac{P_{Harness_N}}{P_{fluid} \times \text{Betz limit}} \times 100 \quad (14)$$

- 5 Commercial scale wind turbines achieve at peak efficiency of 75% to 80% over the Betz limit
6 [36]. As shown in Fig. 8, the estimated power conversion efficiency rises with increasing number
7 of cylinders. For the region of $0.83\text{m/s} < U < 1.08\text{m/s}$, the power conversion efficiency of the
8 four cylinders is larger than 70% regardless of the center-to-center distance and the maximum
9 value is 88.6% at the flow speed of 1.08m/s which is comparable to the peak efficiency of the
10 wind turbine. For the four cylinders, the power conversion efficiency in $U > 1.12\text{m/s}$ is 30~40%.

Figure 8. Power conversion efficiency and power harness efficiency

4.3. Estimation of Power-to-Volume Density

For the estimation of the power-to-volume density, a three-dimensional configuration is used as shown in Fig. 9.

Figure 9. Configuration of cylinder array for power density calculation

The power-to-volume density is estimated based on the converted power by the four-cylinder in tandem array. For the selected cylinder configuration, six cylinders are included in the volume of

18BDL. This configuration is different from the staggered configuration used in previous studies [28, 29]. In the region of $0.79\text{m/s} < U < 1.12\text{m/s}$, the synergy scale, which was experimentally measured, showed that the multiple-cylinder in tandem array can harness more energy than the four cylinders in hydrodynamic isolation. Moreover, the synergy scale of the four cylinders is still around 0.8 in the galloping region even with the center-to-center distance of $2.5D$. This results in significant increase in the power-to-volume density of the Converter. Based on the estimation of the power converted by the four cylinders, the power-to-volume density is calculated as,

$$PVD\left(\frac{W}{m^3}\right) = \frac{\left(\frac{P_{VIVACE-4}}{4}\right) \times 6}{3B \times 6D \times L} \quad (15)$$

where B is the in-stream center-to-center distance between cylinders. For the multi-cylinder Converter, the power-to-volume density is estimated and plotted in Fig. 10. The power-to-volume density increase as the center-to-center distance decreases. For the given tandem array with the center-to-center distance of $2.5D$, the six cylinders are included in the fluid volume of $45DL$ while the staggered configuration used in the previous estimation of the power-to-volume density [28, 29], only two cylinders were included in a volume of $40D^2L$. The power-to-volume density estimated using the previous staggered configuration was 341.43W/m^3 at $U=1.45\text{m/s}$ [29]. At the same flow speed, the value estimated using the tandem configuration in this work is 874.7W/m^3 , which is 2.56 times larger than the previous estimation. To put this into perspective the power density of a large wind farm is 0.01W/m^3 at the rating wind speed of 12m/s [29], which is equivalent to water speed of 1.28m/s . Moreover, at the flow speed of 1.0m/s the power-to-volume density is about 400W/m^3 with 85% power conversion efficiency. This result shows that the VIVACE Converter is a real three-dimensional energy absorber capable of harnessing more energy with its elements in close formation than in isolation. This results in having high power-to-volume density and power conversion efficiency and even working at a river current slower than 1.0m/s .

Figure 10. Power-to-volume density of four PTC-cylinder VIVACE Converter

This paper showed many advantages of the multi-cylinder VIVACE Converter on harnessing horizontal hydrokinetic energy. All studies, however, on the Converter have been done in fresh water so far and never been tested in the ocean. Thus, there are still challenges left to be addressed for the converter to operate in ocean conditions. Common issues for most of the ocean hydrokinetic converters corrosion and extreme environmental conditions. For the Converter, one of the most critical concerns is the corrosion and encrustations on the cylinder surface because those would modify the effect of the PTC and the hydrodynamic phenomena around the cylinders, and result in reduction of the power conversion efficiency. Another challenge in operation is the uniformity of the sea currents along the cylinder axis because it could cause the oblique vortex shedding which reduces the lift force compared to the parallel vortex shedding [37]. These two important concerns should be investigated and solved for the Converter to work efficiently in a real ocean environment.

5. CONCLUSIONS

1 The major conclusions of this study are the following:

- 2 (a) The VIVACE Converter is a real three-dimensional MHK energy absorber because, when
3 designed and built with multiple oscillators, their PTC cylinders work synergistically
4 converting more hydrokinetic power to mechanical in the oscillators than the same number of
5 cylinders operating in hydrodynamic isolation.
- 6 (b) A synergy scale was introduced, which was calculated based on tests conducted in the
7 LTFSW Channel of the MRELab of the University of Michigan. The synergy scale was
8 found to be greater than one in the flow-speed range of $0.8 \text{ m/s} < U < 1.12 \text{ m/s}$ or reduced
9 velocity range of $8.2 < U^* < 11.6$.
- 10 (c) Oscillators in the Converter can be placed in close formation and, thus, provide a boost to the
11 Achilles heel of all renewable energy technologies which is low power density. Other devices
12 when placed one behind the other need large spacing to achieve high efficiency in all but the
13 leading element in the array.
- 14 (d) High power-to-volume density and high power conversion efficiency was achieved by the
15 multi-cylinder Converter even in river or ocean currents as slow as 1.0 m/s , where marine
16 turbines don't work efficiently.
- 17 (e) Hydrodynamically, there is no upper limit for the flow speed for the operation of the
18 Converter because it utilizes the galloping phenomenon, which is an aero/hydro-elastic
19 instability and the oscillatory amplitude increases until the structure fails. The maximum
20 power conversion efficiency of the four-cylinder Converter was estimated at 88.6% of the
21 Betz limit at flow speed of 1.08 m/s , which is comparable to the peak efficiency of an isolated
22 wind turbine.
- 23 (f) The power-to-volume density of the four-cylinder Converter at flow speed of 1.45 m/s
24 reached 875 W/m^3 .
- 25 (g) VIVACE Converter can harness energy from rivers and ocean current as slow as 0.8 m/s -
26 1.5 m/s , with no upper limit. The vast majority of current speeds fall in that range, where most
27 of marine turbines don't work efficiently.

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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)

$E_{VIVACE_N} = \sum_{i=1}^N \left(\frac{1}{2} K A^2 + \int_0^T c_{sys} \dot{y}^2 dt \right)_i$: Converted energy by N -number of the cylinders (J)

f_{osc} : Oscillation frequency of the cylinder (Hz)

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

$m^* = m / m_d$: 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)

- 1 $PVD\left(\frac{W}{m^3}\right) = \frac{\left(\frac{P_{VIVACE_4}}{4}\right) \times 6}{3B \times 6D \times L} : \text{Power-to-volume density (W/m}^3\text{)}$
- 2 $S_{synergy} = \frac{E_{VIVACE_N}}{N \times E_{VIVACE_1}} : \text{Synergy scale}$
- 3 $T : \text{Period of oscillation (sec)}$
- 4 $t : \text{Time (sec)}$
- 5 $U : \text{Flow speed (m/s)}$
- 6 $U^* = \frac{U}{f_{n,w} D} : \text{Reduced velocity}$
- 7 $y(t) : \text{Displacement of the cylinder (m)}$
- 8 $\dot{y}(t) : \text{Velocity of the cylinder (m)}$
- 9 $\zeta_{sys} : \text{System damping ratio}$
- 10 $\eta_{mech} : \text{Mechanical power efficiency (\%)}$
- 11 $\eta_{convert} : \text{Power conversion efficiency (\%)}$
- 12 $\eta_{harness} : \text{Power harness efficiency (\%)}$
- 13 $\rho : \text{Density of a fluid (kg/m}^3\text{)}$