FINAL SCIENTIFIC/TECHNICAL REPORT

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2. Distribution Information*:* No distribution limitations.

3. Executive Summary

Vortex Hydro Energy is commercializing a University of Michigan patented MHK device, the VIVACE converter (Vortex Induced Vibration Aquatic Clean Energy). Unlike water turbines, it does not use propeller blades. Rather, river or ocean currents flow around cylinders causing them to move up and down in Flow Induced Motions (FIM). This kinetic energy of the cylinder is then converted to electricity. Importantly, the VIVACE converter is simpler in design and more cost effective than water turbines.

This project accelerated the development of the VIVACE technology. Funding from the DOE enabled VHE to accelerate the development in three ways. One was to increase the efficiency of the hydrodynamics of the system. This aided in maximizing the power output for a wide range of water speeds. The second was to design, build, and test an efficient power take-off (PTO) that converted the most power from the VIVACE cylinders into electricity. This effort was necessary because of the nature of power generated using this technology. Although the PTO uses off-the-shelf components, it is specifically tuned to the specific water flow characteristics. The third way the development was accelerated was by testing the improved Beta 1B prototype over a longer period of time in a river. The greatest benefit from the longer open-water testing-period is a better understand of the power generation characteristics of the system as well as the maintenance lifespan of the device.

Renewable energy generation is one of today's most challenging global dilemmas. The energy crisis requires tapping into every source of energy and developing every technology that can generate energy at a competitive cost within the next 50 years. Development of VIVACE will bolster domestic energy security and mitigate global climate change. There are numerous commercial and military applications for a fully developed system, which could generate clean/renewable energy from small scale (1-5kW) to medium scale (500kW) to large scale (100MW). Applications span from small portable devices, to direct water pumping for irrigation, direct pumping for desalination, off-shore stations, idle ships, coastal naval bases, coastal communities, and utility companies. Large areas with no natural resources such as the Caribbean or the Polynesia, sparsely populated areas like Alaska, long slow flows like the Netherlands channels, areas that need desalinated water, need VIVACE as a reliable and environmentally compatible technology to generate MHK Power.

4. Introduction

Vortex Hydro Energy is commercializing a University of Michigan (UM) patented MHK device [6-10], the VIVACE converter (Vortex Induced Vibration for Aquatic Clean Energy). Unlike water turbines, it does not use propeller blades. Rather, river or ocean currents flow around cylinders causing them to move up and down in Flow Induced Motions (FIM). This kinetic energy of the cylinder is then converted to electricity. Importantly, the VIVACE converter is simpler in design and more cost-effective than a water turbine. Vortex Hydro Energy is unique in that it is the only company using the physical phenomena of vortex induce vibrations and galloping (both are forms of Flow Induced Motion or FIM) to generate energy from river and ocean currents. Most competitors use some form of propeller-based water turbine.

(1) *(2)* *(3)* *(4)*

Figure 1*: Lab (1) and Open water (2-4) installation of VIVACE devices at varying scales*

5. Background

The VIVACE converter is a transformational technology. It taps into a vast new source of clean and renewable energy, that of water currents as slow as 2 to 3 knots previously off limits to conventional turbine technology that target rivers and ocean currents with water speeds greater than 4 knots. The vast majority of river/ocean currents in the United States are slower than 3 knots and typical rivers are slower than 2kn. Vortex Induced Vibration (VIV) is an extensively studied phenomenon where vortices are formed and shed on the downstream side of bluff bodies (rounded objects) in a fluid current. The vortex shedding alternates from one side of a body to the other, thereby creating a pressure imbalance resulting in an oscillatory lift (Figure 2).

Vorticity/circulation/lift generated by circular cylinders may appear exotic to people because we live in air and see only lifting surfaces (bird/airplane wings, sails, propellers, etc). In reality, however, most objects moving in fluid have a bluff body with some surface roughness and a tail; from tiny (sperm) to gigantic (whale) objects. VIVACE emulates marine life kinematics, which makes it environmentally compatible.

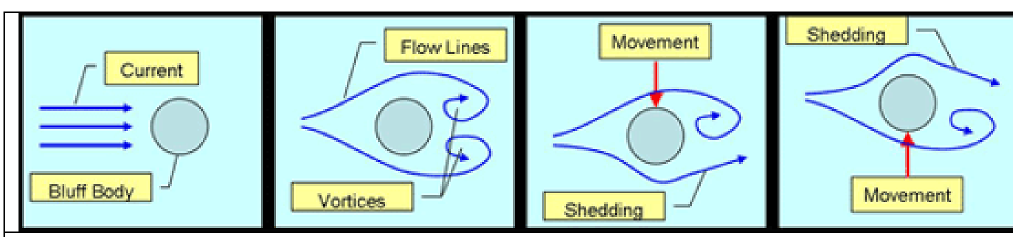


Figure 2: **VIV Cylinder Motion**

Past research and development has resulted in the development of a device that is capable of harnessing this natural power of VIV in a controllable manner, resulting in generation of clean and renewable electric power in an environmentally compatible way. VIVACE can be placed in a river or ocean current to extract energy from moving water. This converter is unlike any existing technology, as it does not use turbines, propellers, or dams. VIVACE converts the horizontal hydrokinetic energy of currents into cylinder mechanical energy. The latter is then converted to electricity through electric power generators. Cylinder oscillations are rather slow – about a cycle/sec - creating no direct physical threat to fish. On the contrary, several studies have been conducted in the past establishing that fish thrive in the wake of a cylinder in a flow. Fish relax in the oscillatory wake and with minimal effort stay behind the cylinder and are in general more active and spawn more. Most notable is the study by Harvard, MIT, and ORNLab [2,3]. More environmental studies need to be conducted for permitting in the USA including noise, electromagnetic interference, and fish strikes. The latter is not an issue for VIVACE. The other two elements need to be investigated in spite of the slow oscillations of VIVACE.

VIVACE's fundamentally different nature is manifested in several ways but the most important one is its three-dimensional nature. Horizontal or vertical hydrokinetic energy converters may be point absorbers (buoys), line attenuators (Pelamis), surface absorbers (Oscillating Water Columns) or area absorbers (turbines) while VIVACE is a genuine 3-D absorber. Cylinders can be distributed in all three dimensions increasing power density while reducing the turbulence generation gradient thus reducing the indirect impact on the marine environment as well.

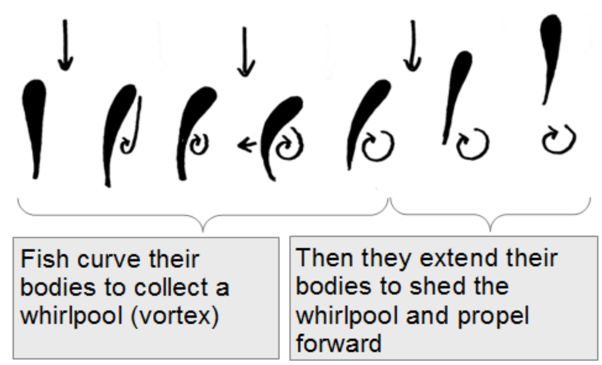


Figure 3: Fish use VIV to swim

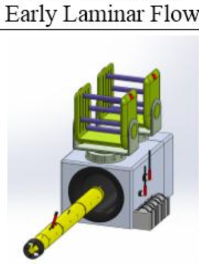
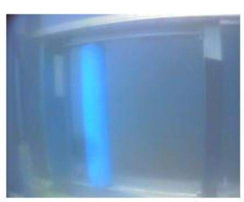
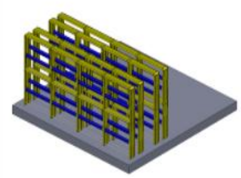
Scale	Scale 1 1,000≤Re≤20,000 Early Laminar Flow	Scale 2 20,000≤Re≤300,000 Late Laminar Flow	Scale 3 300,000≤Re≤500,000 Critical to Turbulent	Scale 4 500,000≤Re Post Super-Critical
Unit				
Applic.	UUV, Sensors, Tracking, Pollution, Weather, Fish, Defense	Portable, Naval Expeditions, Camps	Remote communities, Lighthouses, Naval Operations	Utility Scales, Coastal Communities, Islands

Figure 4*: **VIVACE Scales and Applications***

Vortex Hydro Energy (VHE) has established an overall company objective to develop the VIVACE converter from its prototype developmental status to a viable commercial product that is deployable in rivers/oceans.

6. Results, Discussion, and Accomplishments

Project Objectives:
At the start of the project, the technology readiness level of the VIVACE converter was TRL 4. The objective of the project was to complete DOE TRL 5/6 at the conclusion. VHE has made tremendous progress in developing VIV technology to work effectively over a large range of water current speeds (2 to 8+ knots). The next step was to improve the efficiency of the power takeoff (PTO) system. The objectives of the proposed work pertained to improving the efficiency of the two specific areas of VIVACE's power takeoff system that held most promise:

1. Increase the conversion efficiency from hydrokinetic energy to cylinder kinetic energy. Maximize power output for a wide range of current speeds with the following parameters: spring stiffness, damping coefficient, and system mass.
2. Increase the conversion efficiency from the cylinder kinetic energy to electric energy generation. Redesign the two components of the power take-off system that are the greatest source of inefficiency: rotational generator and the one-way gear/bearing mechanism.
3. Perform open water testing on an improved VIVACE system that will incorporate the improvements obtained from objectives 1 and 2. Build a new PTO that will be installed in VHE's Beta 1 prototype in the St. Clair River.

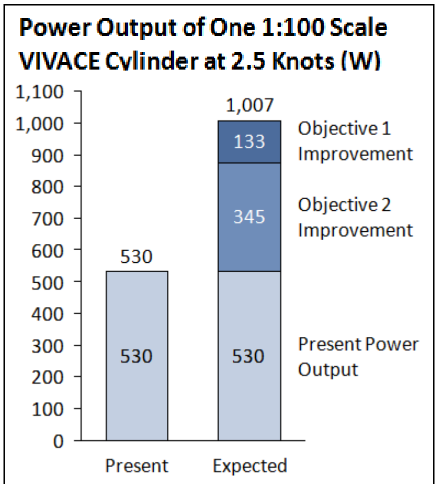
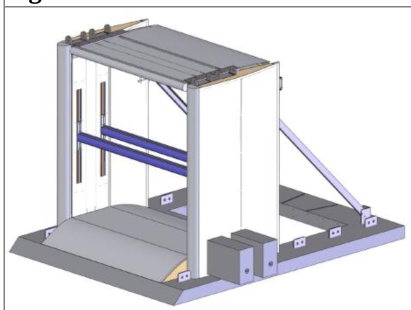
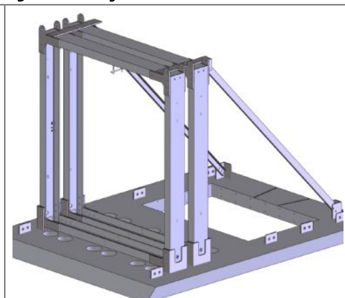
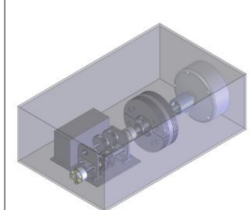


Figure 5: Project Performance Metrics

Objective 1 was expected to increase power output by 25%, while objective 2 was expected to increase power output by 65%.

The major subsystems of the VIVACE system are shown below in Figure 6.

Figure 6: VIVACE converter and major subsystems

			
VIVACE converter Horizontal cylinders move up and down to generate electricity	**Structure subsystem** Major components: metal frame and concrete base	**Hydrodynamic subsystem** Major components: horizontal cylinder	**PTO subsystem** Major components: gears and generator

Overall Project Accomplishments:

1. With improvements in the hydrodynamics and PTO subsystems (Tasks 1 and 2) VHE reached 91% of its goal. (Seen in Figure 5)
2. VHE has made significant strides in optimizing the hydrodynamics of the VIVACE system.
3. VHE has made several improvements to the PTO System.
4. VHE has gained deployment experience with the Beta 1B system in the St. Clair River, and has found a potential maintenance issue, and solved it with the Graphite-Based Bushing design.

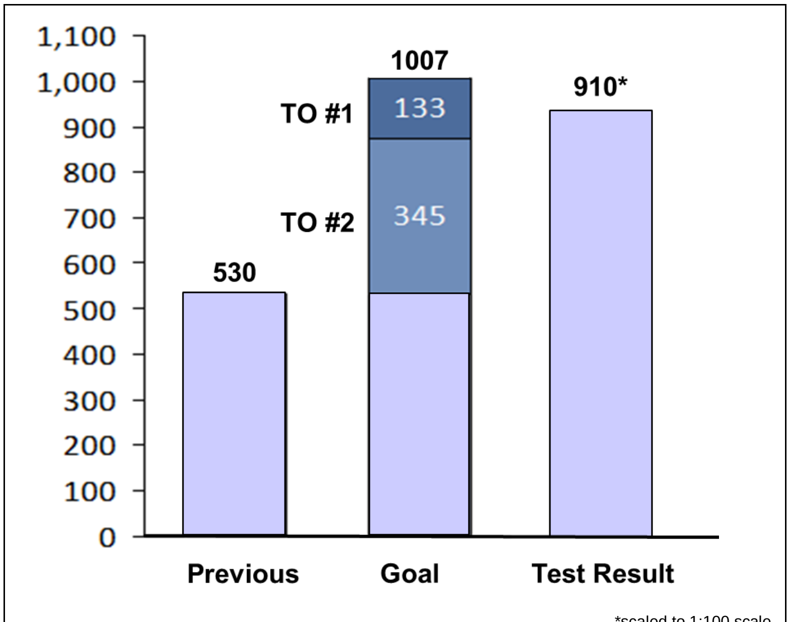


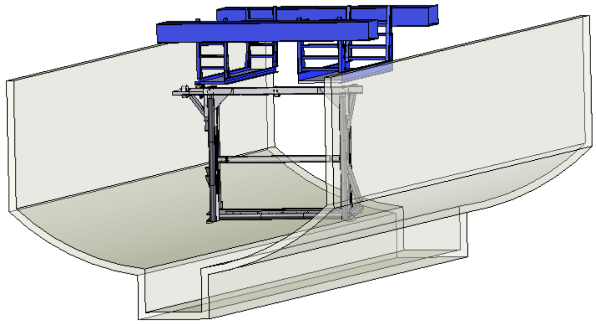
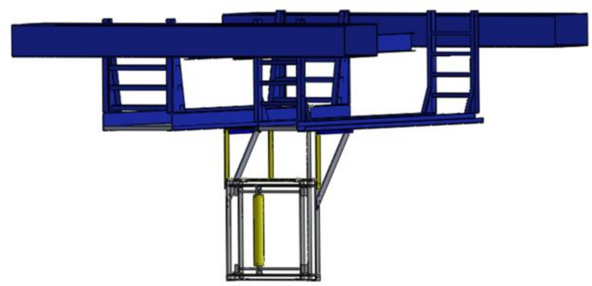
Figure 7: **Overall Project Performance Metric and Result**

Summary of Project Activities

TASK 1: Increase the conversion efficiency from hydrokinetic energy to cylinder kinetic energy. Maximize power output for a wide range of current speeds.

Subtask 1.1:

This subtask was completed by Vortex Hydro Energy at the University of Michigan Towing Tank. VHE completed the m* optimization testing using both the Alpha 7 and Gamma 1 prototypes. The Alpha 7 and Gamma 1 are shown in Figure 8 and Figure 9. The mass ratio of the system m*, is very important in Flow Induced Motions (FIM) and consequently to the VIVACE Converter. m* is the oscillating mass divided by the displaced mass of the system. Tests were performed to find the effect of mass ratio m* on FIM for optimum power generation.

	
	
Figure 8: Alpha 7 Prototype	**Figure 9: Gamma 1 Prototype**

The Alpha 7 prototype was used to test m* values of 1.0, 0.75, and 0.50. In order to test mass ratios over 1.0 (the cylinder will sink) and under 1.0 (the cylinder is buoyant), VHE had to create a pretension with springs to center the oscillation of the cylinder on the device. This is a difficult process, and can drastically reduce the life of the springs. The decreased life of the springs is detrimental to the operations and maintenance of the device, making it difficult to accurately test the Alpha 7 prototype and many m* values that are greater than or less than 1.0 (neutrally buoyant).

Because of difficulty achieving a low m* with the Alpha 7 prototype, VHE designed and built the Gamma 1 (vertical cylinder) prototype. The vertical cylinder design allowed VHE to test the prototype at an m* of 0.3 without having to compensate for the cylinder buoyancy with the spring forces. The buoyancy force from the lower m* value was counteracted by the linear bearing shafts as opposed to using a pretension in the springs.

The data resulting from the towing tank tests (completed with a 6 inch diameter cylinder that was 60 inches long) are shown in Figure 10, Figure 11, Figure 12, and Figure 13. Figure 10 shows the increased cylinder amplitude for the Gamma 1 prototype. Figure 11 shows the resulting power output of the device due to using a lower m*.

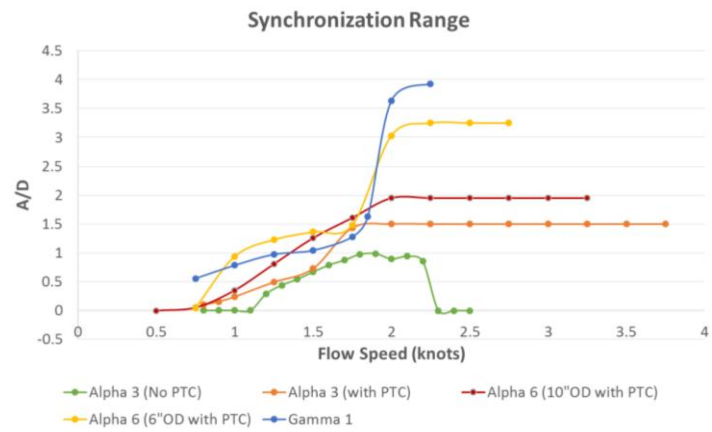


Figure 10: Synchronization Range for VIVACE Prototypes

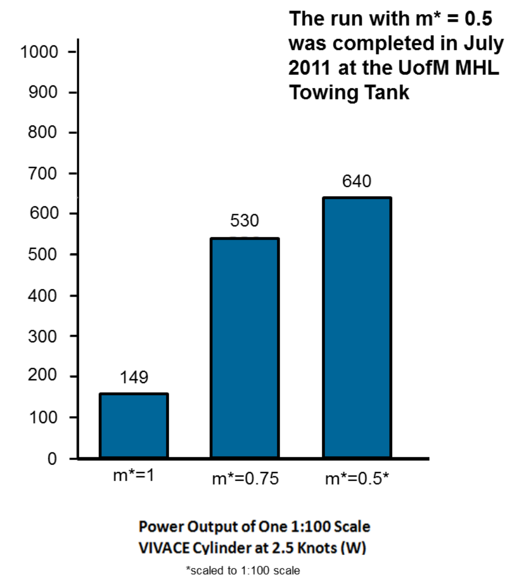


Figure 11: Effect of m* on VIVACE Power Generation

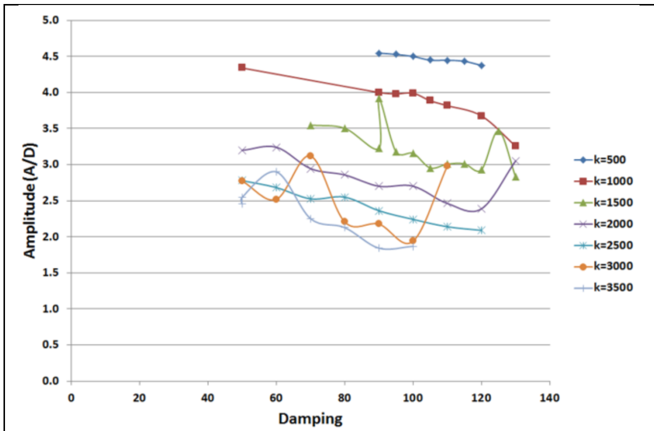


Figure 12: A/D (Amplitude/Diameter) displacement values for multiple spring constants during Gamma 1 towing tank testing at UM @ 2.5 knots

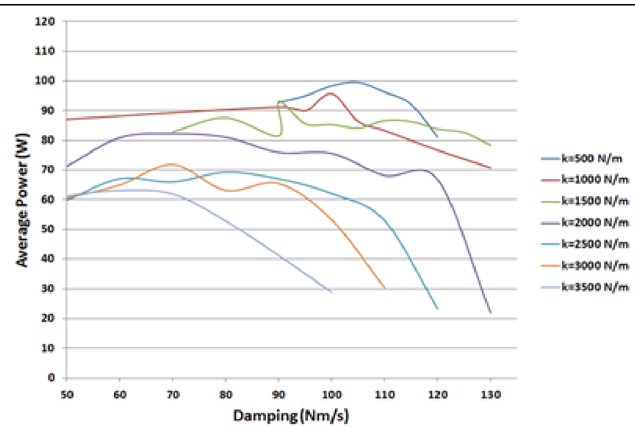


Figure 13: Power values for multiple spring constants during Gamma 1 towing tank testing at UM @ 2.5 knots

Subtask 1.2:

To achieve this objective, VHE and the University of Michigan conducted systematic tests utilizing a new virtual controls technology. The MRELab at the University of Michigan developed a virtual damping-spring system (Vck) for a previous VIVACE project. Vck simulates any value of damping, and spring stiffness without affecting the system hydrodynamics. In the MRELab, Vck makes it possible to assign any value to the energy harnessing damping, and the spring stiffness by inputting the desired value in the computer rather than changing components physically and verifying their values by off-line testing. That is, through a motor/generator, a controller, and a computer, controls are imposed on the system to simulate mechanical components.

Thus, Vck simulates any mechanical VIVACE converter under any type of water current condition. ***The Vck system allows the project team to optimize the parameters of the VIVACE units to operate at their highest efficiency for any predicted water speed condition.*** Under this objective, tests were performed over a broad range of the basic hydrodynamic parameters to find new, better optimized power envelopes that helped increase the already impressive power density of the VIVACE Converter.

The goal of the tests was to establish an operational power envelope for a VIVACE device. Spring Stiffness values of 200 N/m, 400 N/m, 600N/m, 800 N/m, 1000 N/m, 1200 N/m, 1400 N/m, 1600 N/m, 1800 N/m, and 2000N/m were tested. These spring stiffness values were selected based on the size of the cylinders in testing and their corresponding Reynold's numbers. The spring stiffnesses envelope allowed the project team to ensure that for the appropriate Reynolds number, the device was optimized for power generation. A plot of data for A/D (amplitude of oscillation over cylinder diameter), shown in Figure 14, and a plot of data for calculated harnessed power, shown in Figure 15, were developed. The plots show example data with k=1000N/m. The dimensionless damping coefficient values used for these tests were 0.0 to 0.2. These values were chosen so that the entire range of movement (from overdamped – cylinder not moving, to underdamped-no power is taken out of the cylinder) of the cylinders was investigated.

Because VHE had already completed mass ratio (m*) testing on the VIVACE prototype earlier in this project, the m* values in the University of Michigan test matrix were taken out. VHE determined that a lower m* produces more power. UofM tests were done at the lowest m* available for the Alpha 2 prototype.

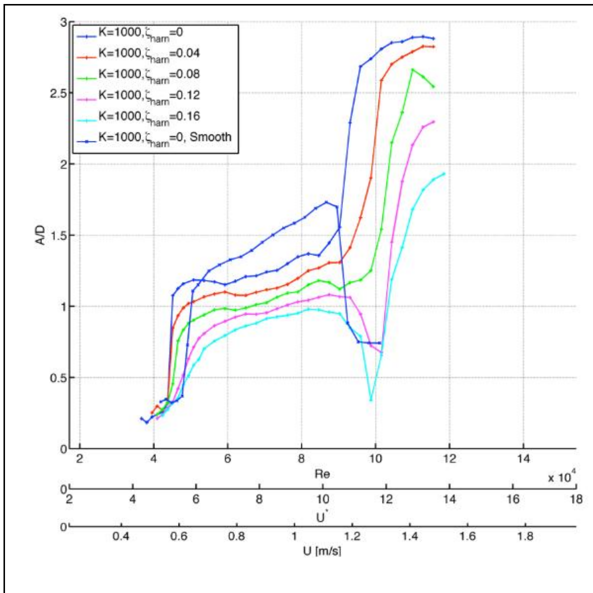


Figure 14: k=1000N/m A/D Test Results

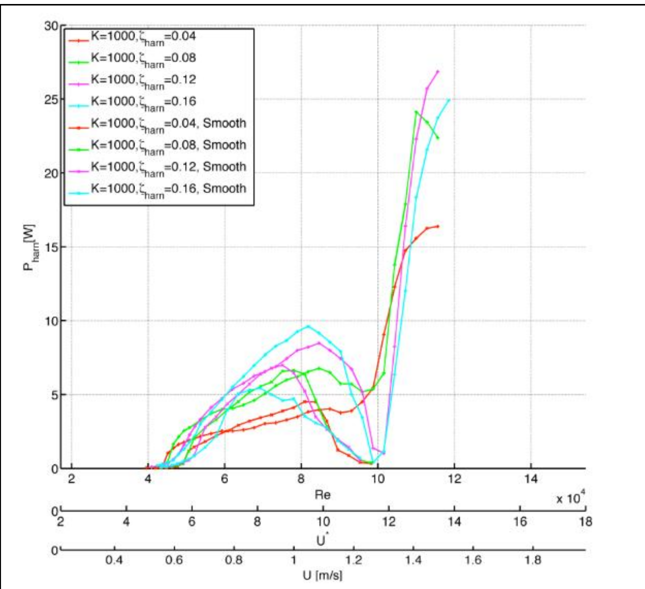


Figure 15: k=1000N/m Harnessed Power Test Results

At the completion of the test matrix for spring constant and damping, a power envelope is constructed. This envelope represents a large operating window for the VIVACE device for various flow conditions at installation sites. With this information, VHE can set the parameters of a device to optimize power generation based on the specific power and site requirements for an individual customer. For example, if VHE had a customer in a new site with a flow speed of 2 knots, the power envelope would show the optimum spring constant and damping value to set the device up with for maximum power generation at that site. If the customer completed a survey and determined that the speed was faster – i.e. 3 knots, VHE would only have to look up the new spring constant and damping value on the power envelope (no need for additional testing to extrapolate power predictions) to ensure that the device was set up appropriately for high effieicncy operation. The power generation curve for this experiement is shown in Figure 16.

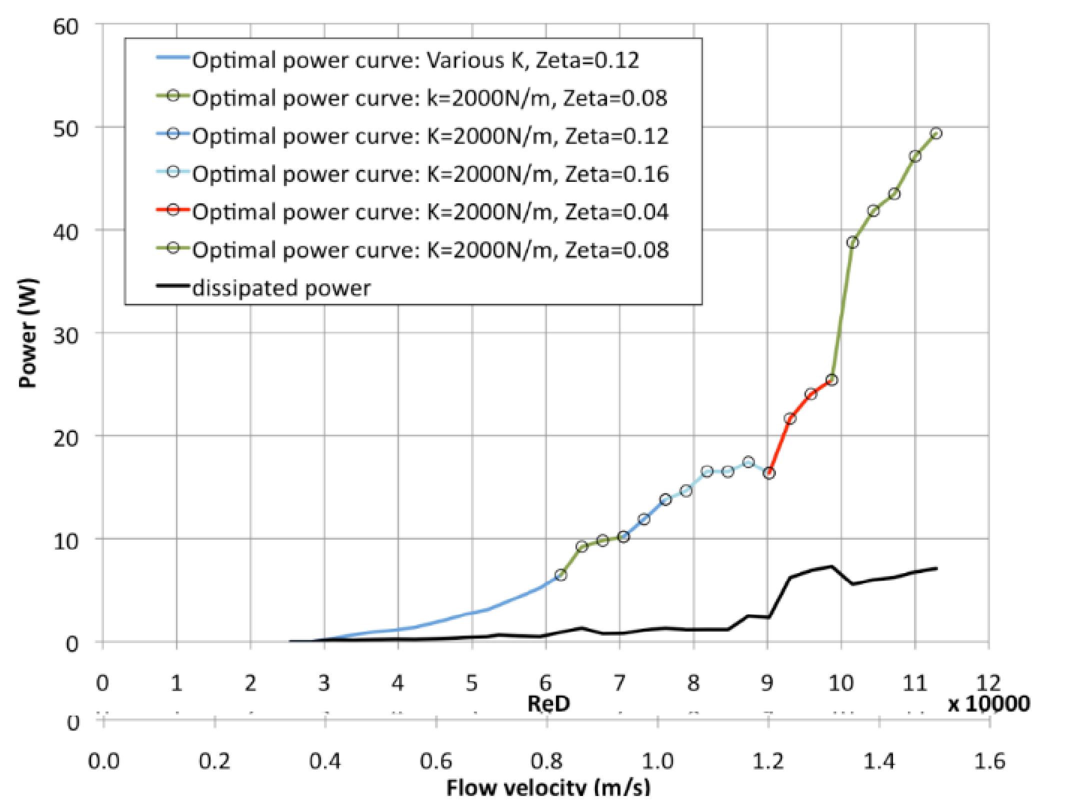


Figure 16: Power Generation Envelope for Alpha 2 Prototype – University of Michigan MRELab

TASK 2: Increase the conversion efficiency from the cylinder kinetic energy to electric energy generation.

The overall performance of the VIVACE system is made up of a complex relationship between hydrokinetic energy, cylinder kinetic energy, and generator electrical damping. What makes VIVACE power a unique and challenging matching problem for the transfer between kinetic and electrical energy is the fact that its power input is non-linear being a derivative of FIM. This makes the system very different from a traditional diesel generator and propeller-matching problem. The VIV power output significantly impacts the generator and vice versa.

The focus of this task was to improve the rotational generator efficiency (includes flywheel and generator size.) The one-way bearing and gear mechanism that converted the bi-directional oscillatory motion of the cylinder to a uni-directional motion was a significant cost factor in the prototype. VHE identified a number of opportunities to lower that cost by redesigning the mechanism. The mechanism also presented an added component of friction and as a consequence, reduced overall energy conversion efficiency. VHE took the current design and modified it to include fewer moving parts.

VHE has fixed problems with efficiency due to misalignment in mechanical pieces, and has lowered the rotational inertia of components for increased efficiency. The most significant losses in the Power Take-Off system in VIVACE were as follows, and all three of these topics were addressed in this project by VHE:

- PTO Rotational Inertia
- PTO Misalignment
- Motor Efficiency, and lack of advanced controls

The first design problem that was overcome in the PTO was reducing the Rotational Inertia. VHE reduced this by either removing the highest sources of inertia, or exchanging them for an equivalent part with lower inertia:

- Flywheel ($J = 1000$ lb*in^2)
  - The flywheel was removed
- 1-Way Rotational Gear Box ($J = 35$ lb*in^2)
  - Replaced with single Gear ($J = 6.7$ lb*in^2)
- Generator ($J = 34$ lb*in^2)
  - Replaced with new generator ($J = 2.8$ lb*in^2)

The second design problem that was overcome in the PTO was reducing misalignment. System damping was reduced by reducing the number of moving parts, and lowering the mechanical friction, and ensuring machining was completed with tight tolerances for better alignment.

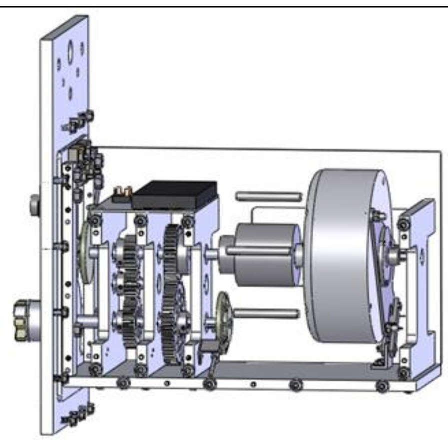


Figure 17: Previous PTO Box

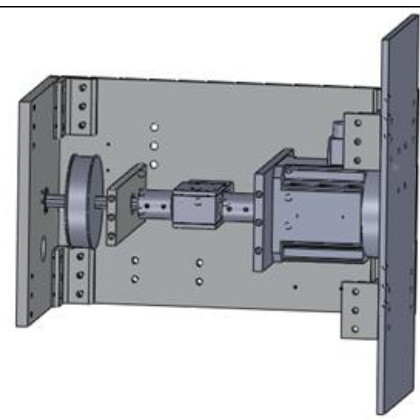


Figure 18: Current PTO Box

After testing, it was observed that the power increased due to the changes made thus far in the project. Figure 19 shows the progress made in power output from Task 2. The m*=0.3 test was completed with the improved PTO box and the Gamma 1 prototype.

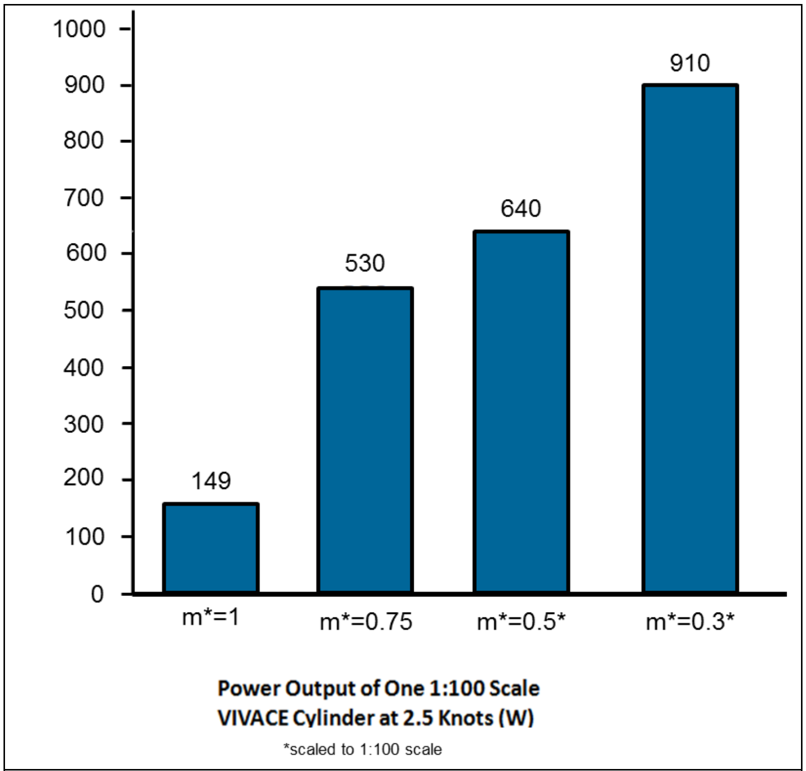


Figure 19: VIVACE Power Output

TASK 3: Perform open water testing on an improved VIVACE system that will incorporate the improvements obtained from objectives 1 and 2. Build a new PTO that will be installed in VHE's Beta 1 prototype in the St. Clair River.

The focus of this task was to perform open water testing on an improved VIVACE system that incorporated the improvements obtained from objectives 1 and 2. This task was broken down into 4 major components: integration, assembly and staging, installation, and recovery.

Integration of PTO and hydrodynamic improvements into the Beta 1 prototype:

The changes to the technology that were discussed in Task 1 and 2 were incorporated and retrofitted into the Beta 1 prototype. All mechanical and electrical design modifications were successfully implemented in the Gamma Prototype. The Beta prototype structure was also successfully updated to retrofit the Gamma prototype inside of it for open water testing.

Figure 20: Gamma 1 Prototype 3D Model

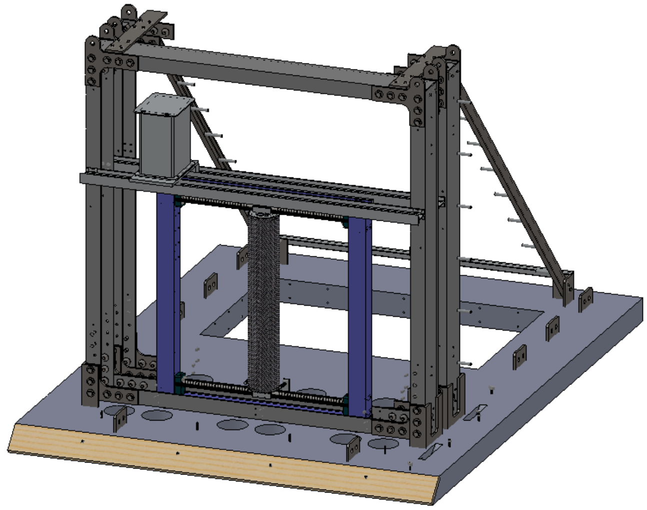


Figure 21: Beta 1B Prototype 3D Model

Design Decisions:

In addition to optimizing the power output of the device, several factors go into the final design of each prototype. In order to ensure a safe and controllable device for the pilot installation for this project, VHE made the design decision to choose a configuration that was less optimized power output in order to better control the cylinder.

The main goal of the river test was to gain knowledge in the survivability, operation and maintenance costs for the device. The focus was then not primarily on maximizing power generation. With previous test results (from Task 2) giving an arrangement for maximum average power generation of 100W for the cylinder, VHE chose a test setup that gave approximately 46 watts for the cylinder at 2.5 knots.

Figure 23 shows the comparison between the maximum power run and the chosen setup for the Beta 1B river deployment. The major factors that reduced the power generation capacity included a different (lower capacity generator), different spring constant, different damping value, and a different sized cylinder. The reduction of power even though VHE used a larger cylinder (6 inches in lab, 10 inches in river) is due to a shorter aspect ratio. In FIM, an aspect ratio lower than 10 (length/diameter) has substantially lower lift force than an aspect ratio greater than or equal to 10. The lab prototype had an aspect ratio of 10, while the river had an aspect ratio of only 6. This reduction in lift force, and subsequently, power was also made to ensure that the project team could use the generator as a break during installation and testing. The project team installed a 2:1 gear ratio in the PTO box to accomplish this goal. By doing this, the device's power efficiency decreased. The Beta 1B results shown in Figure 22 and Figure 23 are used as the baseline laboratory tests for the Beta 1B deployment.

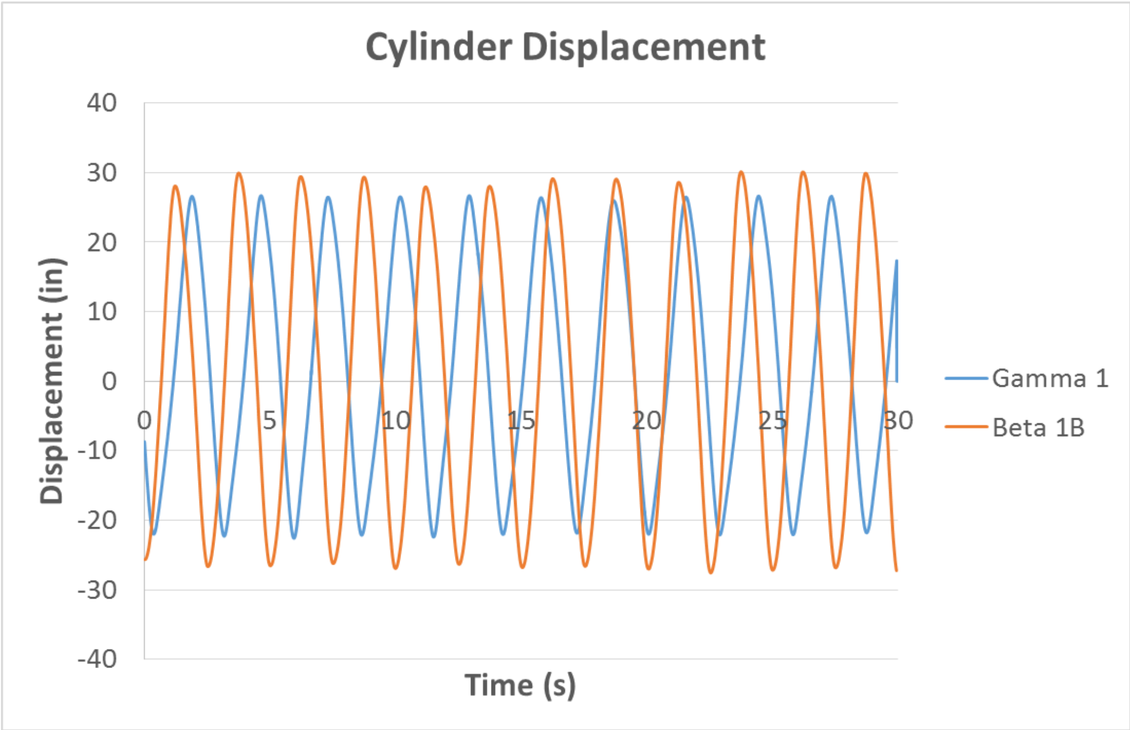


Figure 22: VIVACE cylinder displacement comparison Gamma 1 lab and Beta 1B lab

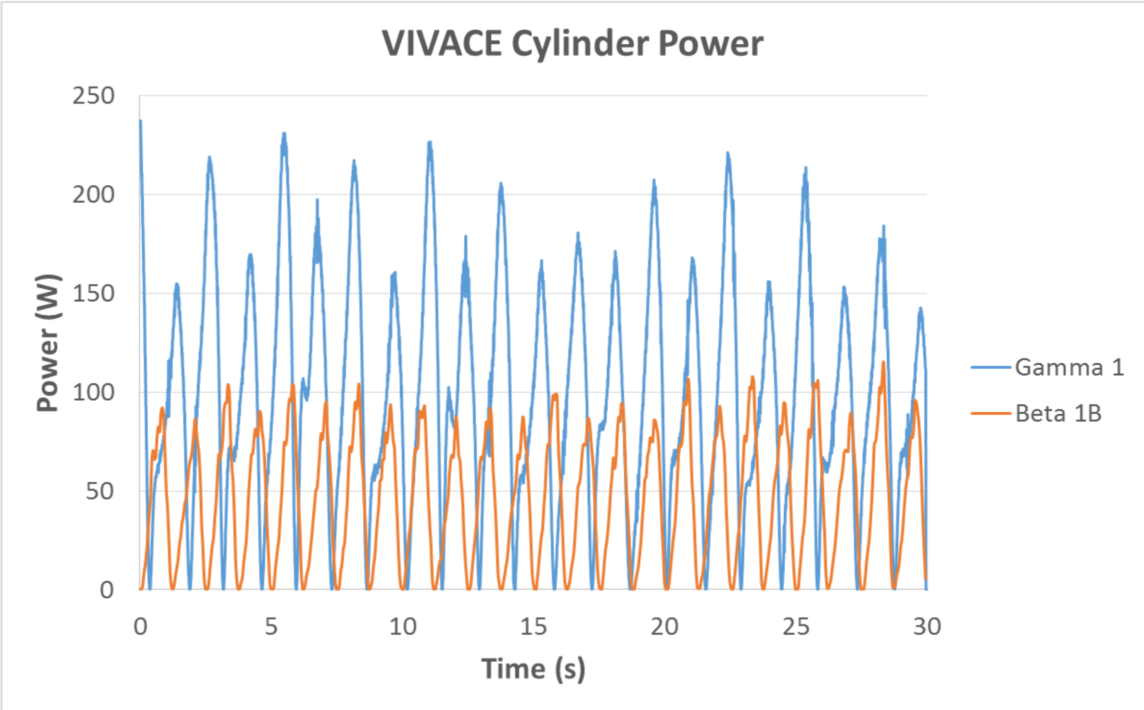


Figure 23: VIVACE cylinder power comparison Gamma 1 lab and Beta 1B lab

<u>Assembly and Staging:</u>

The assembly of the Beta 1B prototype was completed in large, easily shipped pieces, at the VHE offices in Ann Arbor, MI. The pieces were loaded into a rental truck and transported to St. Clair, MI where VHE has access to a dock for full prototype assembly and staging. At the staging location, VHE assembled the components onto the Beta 1 frame and completed bench testing to assure proper operation of the prototype.

<u>Installation:</u>

The Beta 1B Prototype was installed in the St. Clair River in Port Huron, MI. The prototype was installed 90 feet offshore in water that was 20 feet deep. The water speed in the installation location was between 2.0 and 2.5 knots. The installation was successful and the prototype was left in the river to be remotely monitored (video and data feeds). The major installation steps are included below.

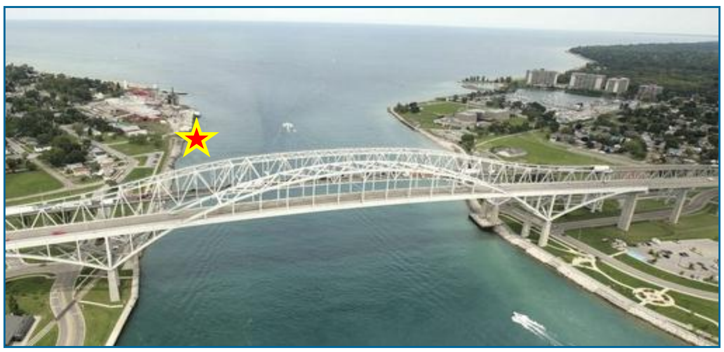


Figure 24: St. Clair River, Port Huron, MI VIVACE Installation Site (Lake Huron to North)

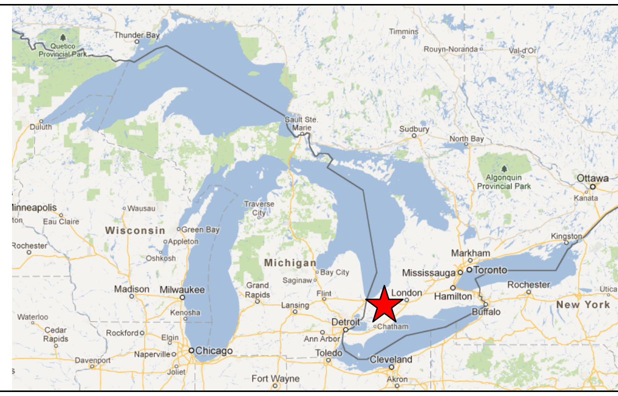


Figure 25: Installation Location, Port Huron, MI

1. Transport from staging to barge – The VIVACE prototype was completely assembled and ready for installation. A barge with a crane on it, along with two tug-boats arrives at the dock. The commercial diving team that is being used for installation arrives with equipment at the dock. The barge ties to the dock. The crane is already on board the barge, and lifts the prototype and diving equipment trailer onto the deck. Once the equipment is loaded and all necessary personnel are on the barge, the barge disengages from the dock and proceeds upstream 5 miles to the installation location in Port Huron, MI.

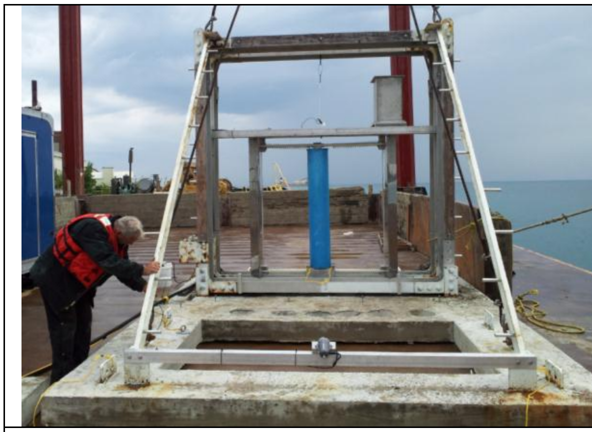


Figure 26: VIVACE Beta 1B Prototype at Staging Dock

Figure 27: Barge and Tugs Moving Crane and Prototype to Installation Location

2. Anchoring and installation attempt #1 – The barge arrived at the installation location approximately 2 hours after leaving the dock. The tugs position the barge in line with the flow approximately 60 feet offshore for install. Once appropriately positioned, the barge drops its anchoring legs. Once anchored, the tugs move away from the barge, and the crane lifts the prototype into the air. The crane lowers the device into the water and uses winches attached to the sides of the prototype to align it. The device is lowered to the riverbed and checked for alignment. During this process, we discovered a large boulder that was directly underneath the prototype. Because of its size and location, the project team had to lift the prototype back out of the water and place it on the barge deck.

3. Installation attempt #2 – The barge was repositioned at 90 feet offshore, and reinstalled the prototype, this time with no boulder in the way, and aligned the device. After the device was aligned, a commercial diver entered the water to assure alignment and to release the lift cables.

Figure 28: VIVACE Beta 1B Prototype Being Lowered in Water By Crane From Barge

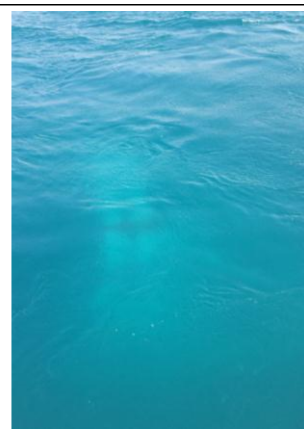


Figure 29: Prototype Installed Looking from Above

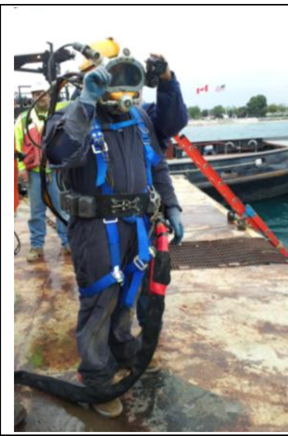


Figure 30: Commercial Diver Installing Beta 1B

4. Power cable delivery to shore and operation- After the device is detached from the crane, the crane then places the power cable weights on the river bed. One of the tugs delivers the power

cable to shore, and it is secured to the shoreline with strain relief cables, and connected to the computer. Once properly connected to the shore computer, the safety mechanisms that were in place on the cylinder to keep it stationary are released, and the cylinder can begin its movement. At this point, the cylinder is operating autonomously. The diver returns to the surface, the tugs reengage with the barge, the anchors are pulled up, and the barge leaves the installation location.

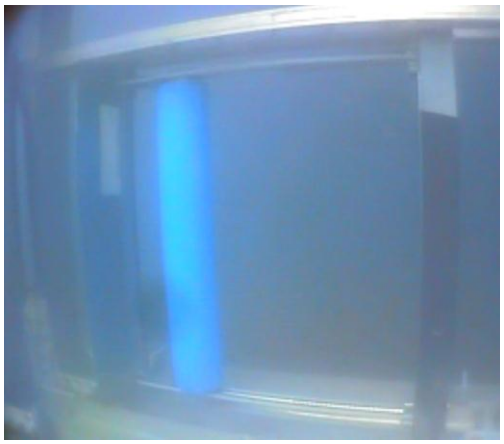


Figure 31: Commercial Diver HeadCam Video Screenshot

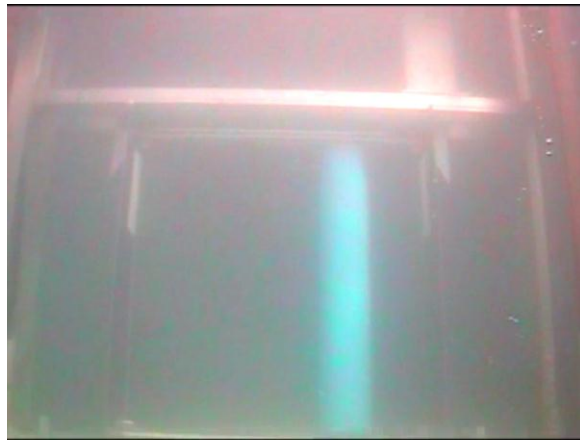
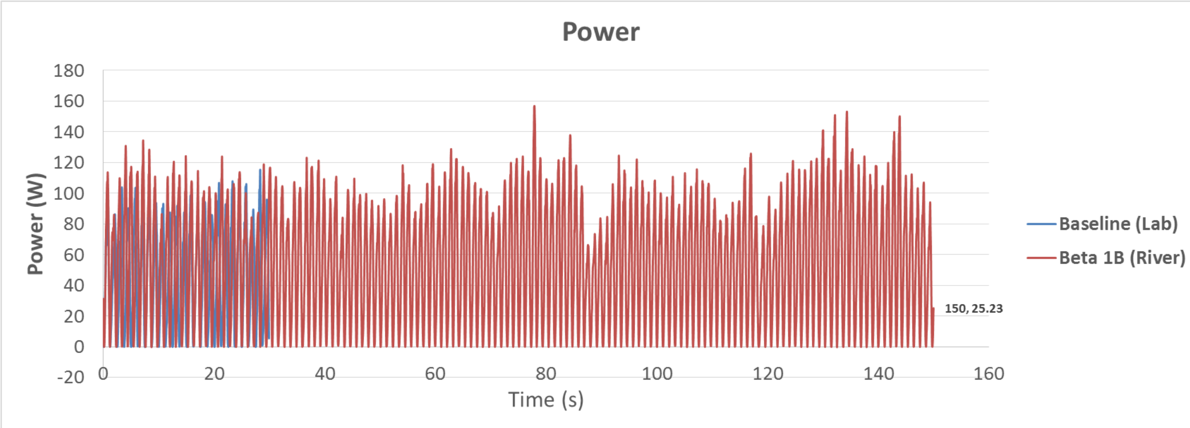


Figure 32: Screenshot from Underwater Camera During Active Testing

Quantitative Installation Analysis:
Figure 33 and Figure 34 show a typical glimpse in time into the data set collected from the Beta 1B river deployment. The plots show the operation of the device and compare it to the Beta 1B lab test baseline.

Testing Parameters Used in Each Test:

Parameter	Beta 1B Lab Test	Beta 1B River Test
Average Water Speed	2.5 knots	2.3 knots
Cylinder Diameter	10 inches	10 inches
Cylinder Length	60 inches	60 inches
Spring Constant	1900 N/m	1900 N/m
Damping Value	5 ohms	7.5 ohms
Gear Ratio	2:1	2:1



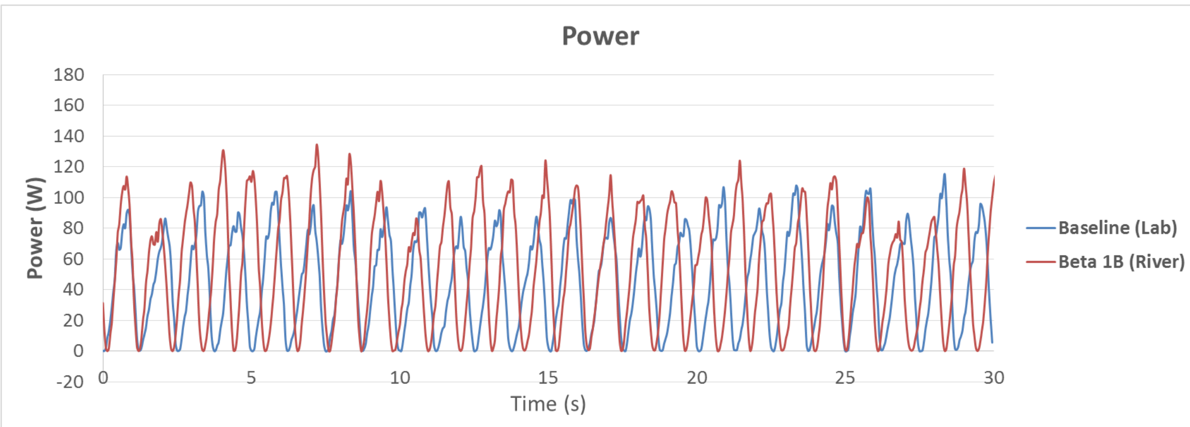
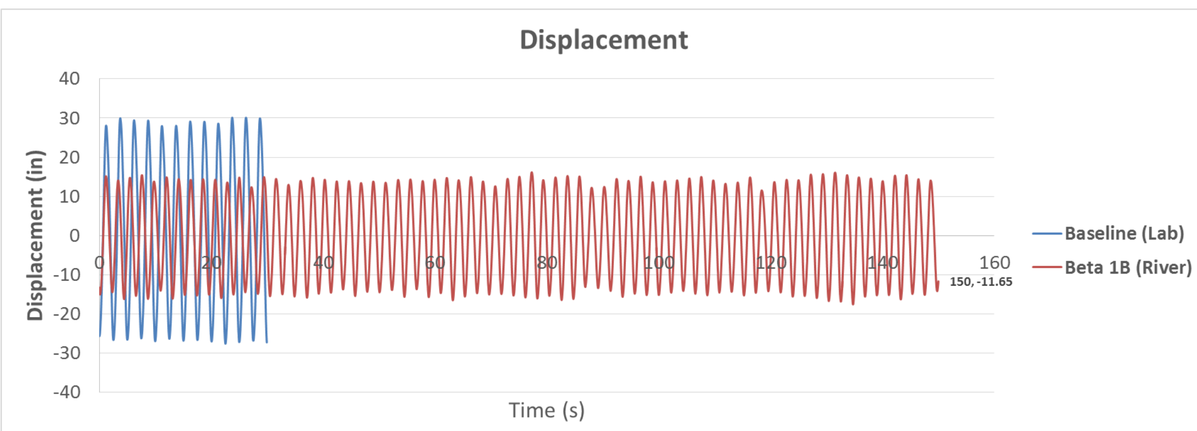


Figure 33: River installation power results compared to lab baseline



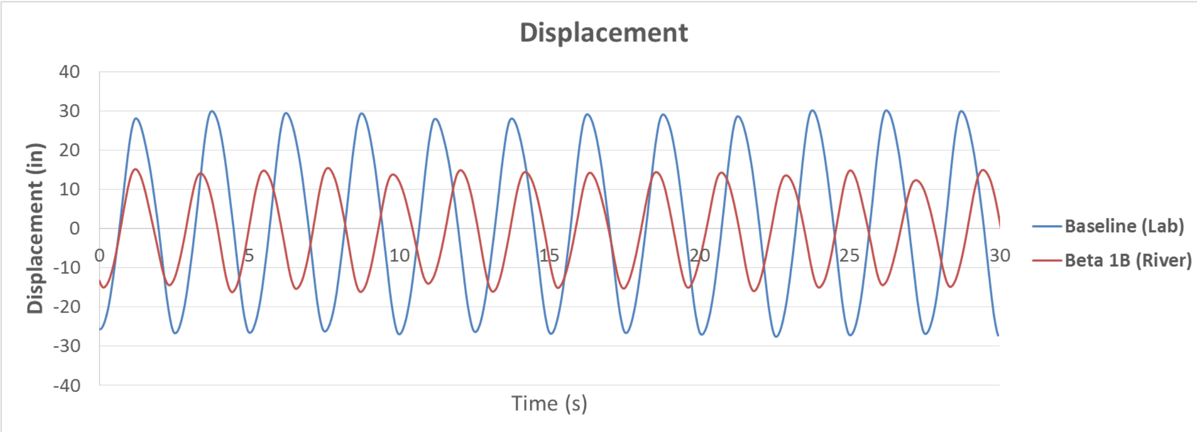


Figure 34: River installation displacement results compared to lab baseline

There are a few small differences in the performance of the devices. The water speed at the installation location was measured to have an average speed of 2.3 knots by the sensor attached to the VIVACE device. This meant that the maximum power generation of the device would be achieved with a different damping value that what was used in lab testing. This value was optimized during the in-river testing and found to be 7.5 ohms. Because of the change in water speed, the oscillation amplitude of the cylinder is seen to be lower in the river than in the lab tests. With these changes, the average power of the device was 51 W. This is close to what was achieved in the lab with similar conditions (46 W). The repeatability of the lab to river scaling is accurate.

This result also indicates that the boundary effects from the tunnel nature of the towing tank and recirculating channel at the University of Michigan do *not* have additive effects that are not accounted for in a river installation. **VHE testing in the laboratory settings is representative of a real installation environment in terms of power performance values.**

Qualitative Installation Analysis:
During the installation procedure, there were two major qualitative qualities that were noted. When a large freighter passed through the shipping channel of the river, the project team observed a decrease in water speed at the device's location. There is an average of approximately 5 barges per day, and the effect they had on the water speed lasted for approximately 30 seconds each time one passed. This amounts to 2.5 minutes of decreased water speed per day, which is minimal. The second note was that there was a change in water speed at the devices location when the barge was located above and upstream of it. When installation was completed and the barge was moved out of the way, the device saw an increased water speed.

VHE also collected underwater video documenting the function of the prototype before the prototype was removed. During constant monitoring, the testing team noticed that the cylinder had stopped oscillating. VHE sent a diving team out to the prototype to try to troubleshoot the problem and get the cylinder moving again for more durability testing. The diving team was not able to revive the device, so a decision was made to remove it.

Recovery:

Upon removal from the river, it was learned that the cause of failure was a bearing malfunction in the linear transmission subsystem. Beta 1B used unsealed radial ball bearings because they had very low damping and increased performance parameters. During testing, sand and other small debris accumulated on the face of the bearings and completely seized the balls. Figure 35 shows two photos of one of the bearings VHE removed from the device post-recovery.

Figure 35: Seized Ball Bearings from Beta 1B River Installation

To fix this problem for future applications, VHE conducted substantial research on a variety of bearings that could be used in an open water environment. VHE consulted with experts in the field and with manufacturers of bearings. The best option found was a graphite based bushing as displayed in Figure 36. Two performance parameters were used in the selection of this bearing, (1) highest bearing life (longevity), and (2) lowest friction. This graphite based bushing provided the best compromise between longevity and friction. It functions by impregnating graphite onto the shaft that rotates about the bearing hole, thus lowering the friction between the bushing and the shaft.

Figure 36: Graphite based bushing

Bearing Test Results:

VHE integrated the selected graphite based bushing (Figure 36) into the prototype design and completed a round of lab testing. This testing was then compared to previous tests where VHE had used radial ball bearings. Photos from testing at the Ohmsett facility for the bearing tests are shown in Figure 37 and Figure 38, respectively.

Figure 37: VHE Testing at Ohmsett in Leonardo, NJ

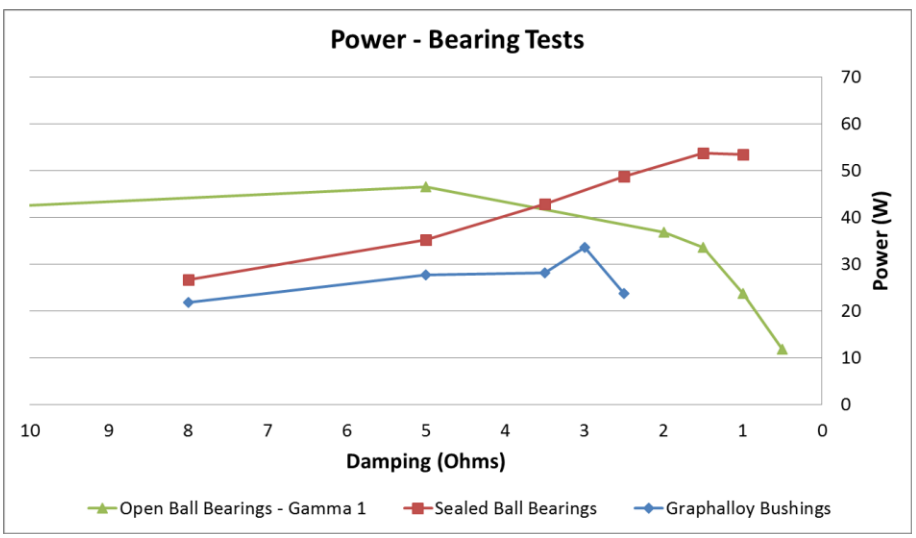


Figure 38: Bearing test comparison completed at OHMSETT (2.5 knot run)

By having this direct comparison, VHE has been able to determine the effect of bearing type on power generation of the VIVACE device. When tested in the wet lab environment, the power drop from using the new bushings was observed to be 29%.

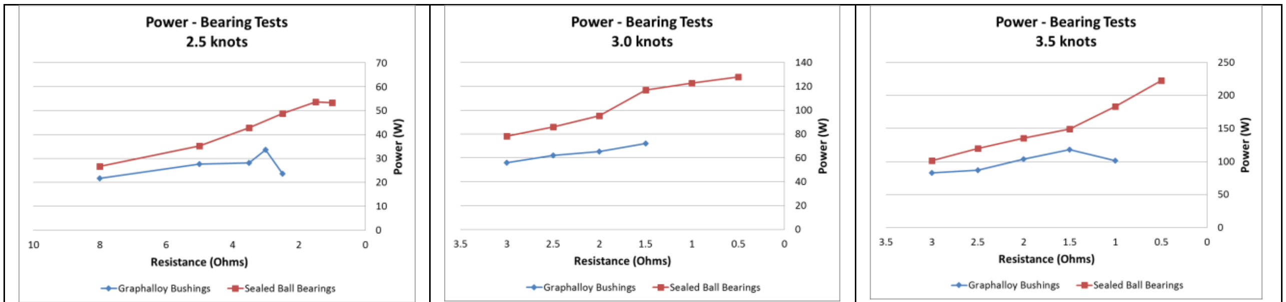


Figure 39: Power Results for 2.5, 3, 3.5 knot bearing tests

VHE concluded that the trade-off of power loss from the graphite-based bearings for increased reliability and maintenance purposes is worth the added longevity/life. VHE will be using the graphite-based bushings in all future tests, until a more effective bushing/bearing can identified. VHE will be actively pursuing more efficient (lower friction) bearings.

Spring Tests:
While at OHMSETT, VHE was also able to complete another set of tests that define the power performance operation window of the Beta 1B device. During these tests, VHE tested to determine the effect of varied spring constants on the power performance. The available spring sizes at the test were 2000, 2520, and 3085 N/m. These springs were stainless steel compression springs. Tests were run through the speeds of 2.5, 3, and 3.5 knots through a full range of reisistance (electrical damping values). **VHE was able to complete a test where the compression springs were completely removed**, and only a short (6 inch) jounce bumper-type spring was installed at the extents of the oscillatory motion.

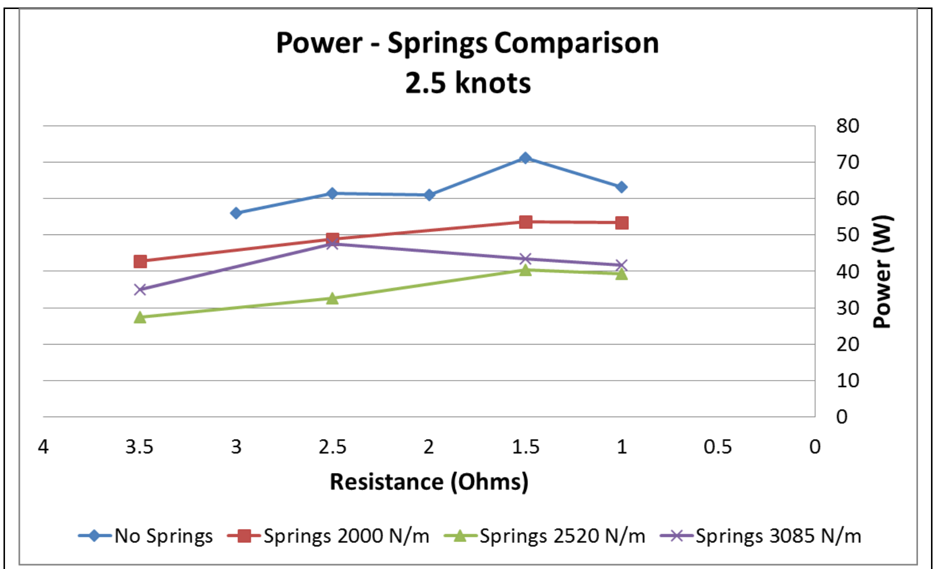


Figure 40: Spring test comparison completed at OHMSETT (2.5 knot run)

The same trend that was noted in Task 1 – hydrodynamic improvements held true in this lab test – the lower spring constants produce higher power. As seen in Figure 40 the spring constant of 2000 N/m produced the highest value for power over the entire range of resistances, and the "no spring" version produced the most power of all of the combinations of parameters.

	Baseline	**No Spring System**
Spring	2000 N/m	N/A
Resistance	1.5 ohms	1.5 ohms
Water Speed	2.5 knots	2.5 knots
Average Power	64 W	71 W

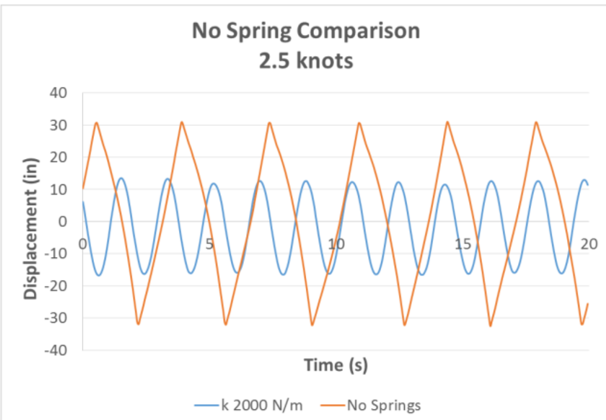


Figure 41: Displacement data from "no springs" cylinder power generation tests at OHMSETT

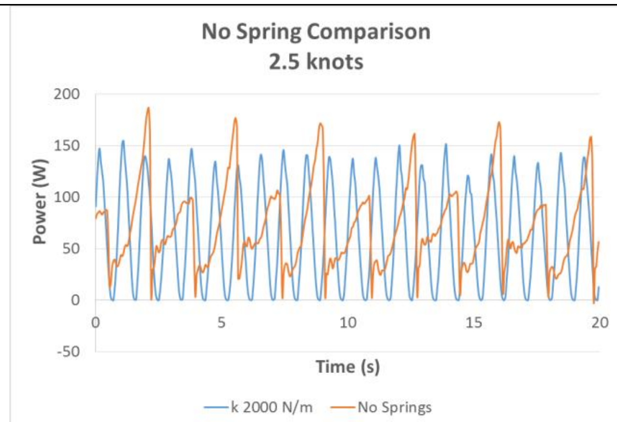


Figure 42: Power data from "no springs" cylinder power generation tests at OHMSETT

The "no springs" system had an increase of average power of 11%! VHE will be investigating the implementation of a "no-springs" or "jounce bumper" system in the next development stage. By removing the springs, VHE is able to increase the device's power output, and increase device life (the springs had the lowest life expectancy of any component in the VIVACE system). This is a win-win situation for the project team.

7. Conclusions

This project accelerated the development of the VIVACE technology. Funding from the DOE enabled VHE to accelerate the development in three ways.

1. Increased hydrodynamic efficiency. The project team increased the efficiency of the hydrodynamics of the system. This aided in maximizing the power output for a wide range of water speeds.

2. Increased power take-off efficiency. The project team designed, built, and tested an efficient power take-off (PTO) that converted the most power from the VIVACE cylinders into electricity. This effort was necessary because of the nature of power generated using this technology.

Although the PTO uses off-the-shelf components, it is specifically tuned to the specific water flow characteristics.

3. Improved Beta 1B Prototype for River Installation. The other way the development was accelerated was by testing the improved Beta 1B prototype over a longer period of time in a river. The greatest benefit from the longer open water testing period is to better understand the power generation characteristics of the system as well as the maintenance lifespan of the device.

4. Partial Benchmarking. It is important to place the output of VIVACE into perspective. All renewable energy technologies suffer from low power density compared to fossil fuel technologies. Power density is usually measured in *actually generated power per weight*. That is measured in kW/ton. There are other measures like rated kW/ton or rated kW per volume, which are helpful but may be deceiving if not interpreted correctly. A very important paper was published in 2012 by the National Technical Norwegian University rating wave energy device actual performance [1]. The results are summarized in the table below and show VIVACE with ballast and without ballast.

Comparison (ranking) of WEC in MOAN paper:

Table 1: ***Numerical benchmarking study of a selection of wave energy converters:***

Device:	Annual Energy Output (kW)	Area (m^2)	Depth (m)	Weight (Mg)	Power-to Volume Ratio (kW/m^3)	Power-to-Weight Ratio (kW/Mg)
F-OWC	371.6	6500	13	1800	0.0044	0.2064
B-HBA	309.4	4350	13	1600	0.00547	0.1933
B-OF	498.6	2020	13	3800	0.0019	0.1312
Bref-HB	3.24	42	40	31	0.00204	0.1045
Bref-SHB	19.86	220	20	200	0.00451	0.0993
F-3OF	108.8	2160	8.5	1622	0.00593	0.06707
F-HBA	338.6	4750	87.5	5233	0.00081	0.0647
F-2HB	193.8	2120	50	5704	0.00183	0.0339

Device Descriptions: Bref-HB- Bottom reference heaving buoy, Bref-SHB- Bottom reference heaving submerged buoy, F-2HB- Floating two-body heaving converter, B-HBA- Bottom-fixed heave-buoy array, F-HBA- Floating heave-buoy array, B-OF- Bottom-fixed oscillating flap, F-3OF- Floating three-body oscillating flap device, F-OWC- Floating oscillating water column

Notes: kW is calculated using the average power output at the five different sites are reported.
m^2 is the characteristic area (area that cannot be used by other WEC)
depth is minimum operating depth of WEC
Mg is the mass of the WEC in mega grams
kW/m^3 is the annual energy output per characteristic volume of the WEC
kW/Mg is the annual energy output per Mg of the WEC

Table 2: ***VIVACE comparison to power-to-weight ratios***

	Device Weight (Mg)	Ballast Weight (Mg)	Output (kW)	Power-to-Weight Ratio (kW/Mg)
1 Cylinder	.2267	8.165	1.2	.1430
2 Cylinders	.4535	8.165	2.9	.3365
3 Cylinders	.6803	8.165	4.2	.4748
4 Cylinders	.9072	8.165	6.0	.6613

*note that it is not accurate to compare VIVACE to the WEC's given in the MOAN papers because VIVACE's power output was not based on the same locations as the others.

Future Work:

In order to **scale the results of this project to a commercial scale**, a suggested module has been designed and shown in Figure 43 – the Oscylator 33. Its performance is shown in the Figure 44. Power output is calculated as function of flow velocity but the unit is assumed to be operating at 3.2 knots to generate 33.3 kW. Higher speeds will generate much more power. Multiple units can be deployed in a single location to form a farm to reach utility scale production, which will attract attention of utility companies near rivers and oceans. The fact that such source can provide base power rather than intermittent as wind, waves, and solar sets the Oscylator 33 in high demand. The possibilities are endless with such a predictable renewable energy source.

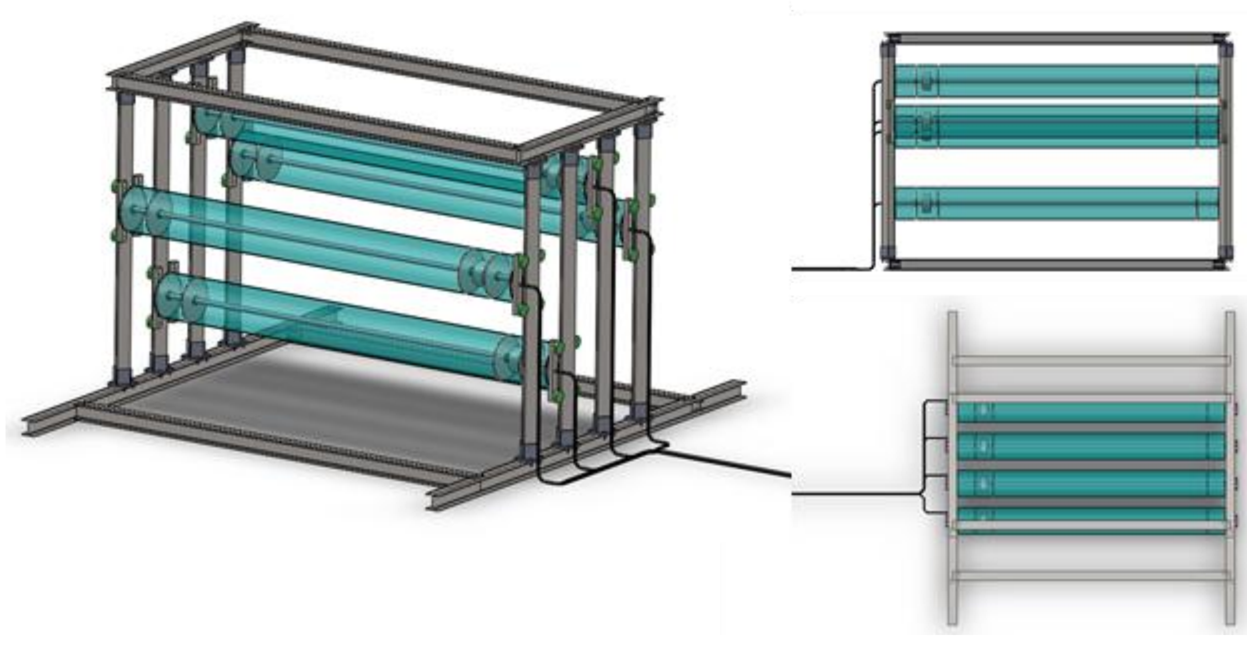


Figure 43: Commercial Scale Oscylator 33 3D Model

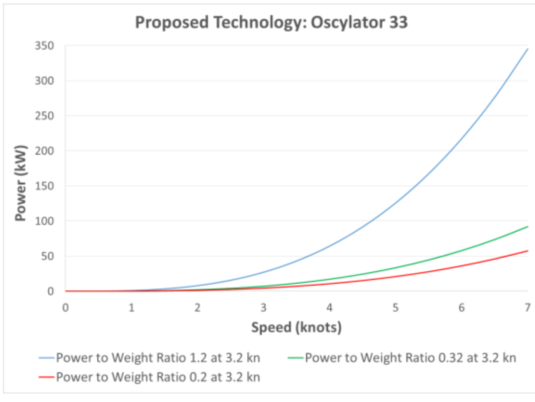
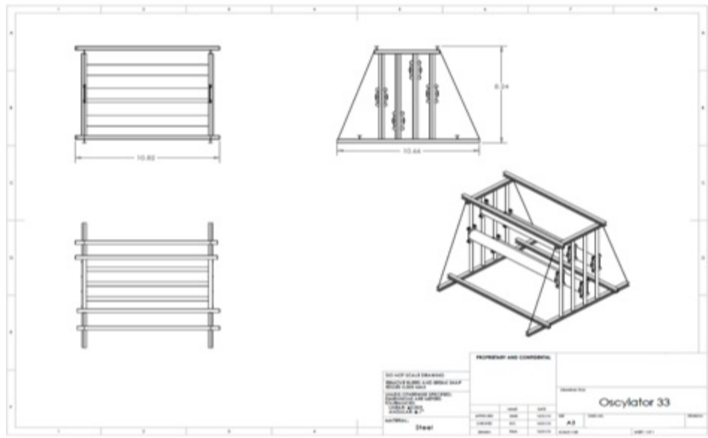


Figure 44: Oscylator-33: Unit designed for river utility scale. 33.3kW actual (not rated) power at 3.2 knots: 4 Horizontal Cylinders in Series; Height = 8.24 m; Length (in flow direction) = 10.66 m; Width = 10.82 m; Weight (w/o ballast): 28 tons

Proposed technology Power/Weight= 1.2 kW/ton
With hydro improvement only P/W= 0.32 kW/ton
State-of-the-art P/W= 0.2 kW/ton



Oscylator 33 Comparison to 1.5MW GE Wind Turbines

	Oscylator 33	GE 1.5 MW wind Turbine
Rated Power	33 kW	1500 kW
Capacity Factor	96%	27%
Actual Power	32 kW	405 kW
Actual Cost to Buy	$4500/kW	$3200/kW
Actual Cost to Install	$310/kW	$3700/kW
Total Cost	$4900/kW	$6900/kW

The next steps for the VHE team to commercialize this device is to achieve multi-body synergistic FIM (what has been demonstrated experimentally as shown in Figure 45). The fundamental area to be pioneered using primarily experiments is: *"Validating estimates of synergistic kinematics of cylinders in schools for the purpose of enhancing their flow induced motions inspired by fish-school biomimetics."*

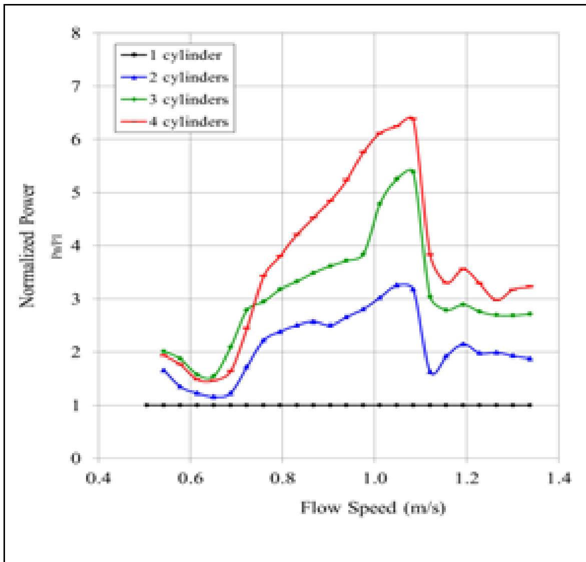


Figure 45: Synergy of 2-3-4 cylinders: School energy is higher than the sum of energies of all individual components.

That is, increase the hydrodynamic power output by a factor of 1.6. One of several changes required to achieve this goal is bringing the cylinders closer. Changing the current practice of 8-10 body lengths center-to-center spacing between cylinders or turbines to 1.5 diameters results in a reduction of occupied volume by a factor of 6. The corresponding weight change for the device shown is 3.75. That results in an increase in power-to-volume ratio by a factor of about 10 and an increase in power-to-weight ratio by a factor of about 6. Such a breakthrough in power density is calculated to reduce the LCOE of the proposed device to an estimate of 8-12¢/kWh.

8. Products Developed Under the Award

a. Publications –

1. Wu W., Bernitsas M.M., Maki, K.J., "URANS Simulation vs. Experimental Measurements of Flow Induced Motion of Circular Cylinder with Passive Turbulence Control at 30,000<Re<120,000," Proceedings of the 30th OMAE 2011 Conf., Paper #50293, Rotterdam, The Netherlands, June 19-24, 2011; Journal of Offshore Mechanics and Arctic Engineering, ASME Transactions, in press 2012.

2. Park, H. R., R. A. Kumar, Bernitsas, M. M., "Enhancement of Flow Induced Motion of Rigid Circular Cylinder on Springs by localized Surface Roughness at $3\times10^4 \leq Re \leq 1.2\times10^5$", Ocean Engineering, in press 2013.

3. Park, H. R., R. A. Kumar, Bernitsas, M. M., "Suppression of Flow Induced Motion of Rigid Circular Cylinder on Springs by Localized Surface Roughness at $3\times10^4 \leq Re \leq 1.2\times10^5$", submitted Journal of Fluids and Structures, December 2012.

4. Ding, L., Bernitsas, M.M., Kim, E. S., "2-D URANS vs. Experiments of Flow Induced Motions of Two Circular Cylinders in Tandem with Passive Turbulence Control For 30,000<*Re*<105,000", Ocean Engineering, in press 2013. http://dx.doi.org/10.1016/j.oceaneng.2013.06.005.

5. Park, H. R., Bernitsas, M. M., Chang, C.C., "Robustness of the Map of Passive Turbulence Control to Flow-Induced Motions for a Circular Cylinder at 30,000<Re<120,000", Proceedings of the 31st OMAE 2013 Conf., Paper #10123, Nantes, France, June 9-14, 2013.

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b. Website or other Internet Site Reflecting Results – Photos and videos from VHE tests completed under this funding are included on the Vortex Hydro Energy website: http://www.vortexhydroenergy.com

c. Networks or Collaborations Fostered– None

d. Technologies/Techniques– None

e. Inventions/Patent Applications, or Licensing Agreements– None

f. Other Products– None

9. Computer Modeling

Not applicable. This project did not involve any computer modeling.

10. References

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