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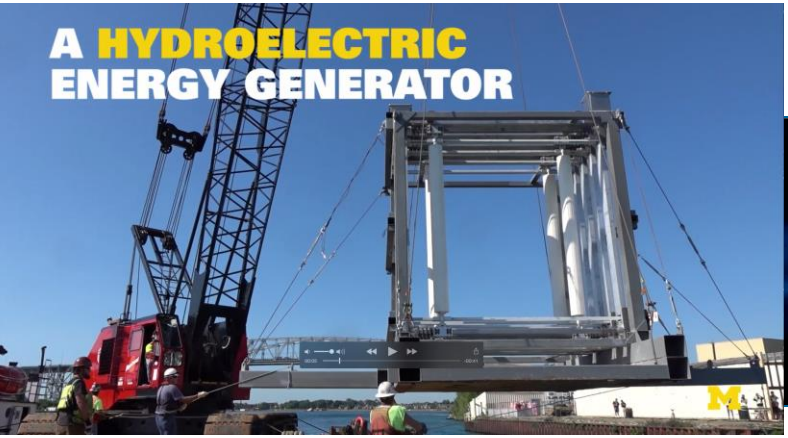

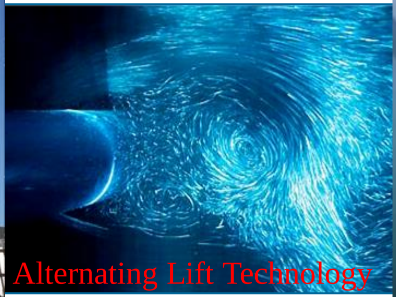

Current Energy Harnessing using Synergistic Kinematics of Schools of Fish-Shaped Bodies

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Current Energy Harnessing using Synergistic Kinematics of Schools of Fish-Shaped Bodies

"Elevator Speech":

• Functions even in slow currents • Alternating Lift Technology (environmental compatibility)
• synergistic flow-induced motions (FIMs) like fish • high power-density (400W/m^3 at 1.3m/s)
• accepted by the local community • can meet the EERE-levelized cost of energy (LCOE) target (¢15/kWh) • site adjustable • flow adjustable with open-ended response amplitude operator

The Challenge: • Complex Hydromechanics • many parameters for school-optimization but great potential for continuous improvement by understanding synergistic FIMs in schools

Partner: Marine Renewable Energy Laboratory, University of Michigan

• World class lab *dedicated* to synergistic multi-body FIMs • Holistic approach with experiments, four virtual oscillators, computational fluid dynamics, visualization, empirical mode decomposition

Program Strategic Priorities

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Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- **Conduct R&D for innovative MHK systems & components**
- Develop tools to optimize device and array performance and reliability
- Develop and apply quantitative metrics to advance MHK technologies

Deployment Barriers

- Identify potential improvements to regulatory processes and requirements
- Support research focused on retiring or mitigating environmental risks and reducing costs
- Build awareness of MHK technologies
- Ensure MHK interests are considered in coastal and marine planning processes
- Evaluate deployment infrastructure needs and possible approaches to bridge gaps

Market Development

- Support project demonstrations to reduce risk and build investor confidence
- Assess and communicate potential MHK market opportunities, including off-grid and non-electric
- Inform incentives and policy measures
- Develop, maintain and communicate our national strategy
- Support development of standards
- Expand MHK technical and research community

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- Improve resource characterization to optimize technologies, reduce deployment risks and identify promising markets
- Exchange of data information and expertise

Project Strategic Alignment

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The Impact

- The Target improvement is to increase marine and hydrokinetic (MHK) energy capture by using synergistic operation of multiple cylinders
  - ✓ Synergistic FIM of multi-cylinder operation has increased the harnessed power by 2.7–7.5 times that of a single cylinder in the Marine Renewable Energy Lab (MRELab) at the University of Michigan.
  - ✓ *Oscylator-4* is a 3D-converter
  - ✓ Volume of *Oscylator-4* reduced by an order of magnitude
  - ✓ Power-to-Volume 400W/m^3 at 1.3m/s
- Impact on Industry – The *Oscylator* will enable the capture of hydrokinetic energy even at low flow speeds
  - ✓ River operation at 1.18m/s (2.3kt)
  - ✓ MRELab start at 0.38m/s (0.74kt)
- Endpoint – test a functional 4kW size device in the St. Clair River in Port Huron

1. Technical Approach

Technical Objective #1: Extensive laboratory-testing to identify efficient 3-dimensional distribution of a school of cylinders

- Lab tests with 1, 2, 3, 4 cylinders in tandem and staggered
  (Parameters: velocity, spacing, stiffness, damping)
- Reveal the underlying hydrodynamics of multi-body interaction
  (18 phenomena: interaction of shear-layers, vortices, and bodies in Flow Induced Motion)
- Achieve synergistic FIM to enhance rather than suppress instabilities
- Holistic approach to fully characterize synergistic FIM in the MRELab, which studies this problem exclusively
- Unique:

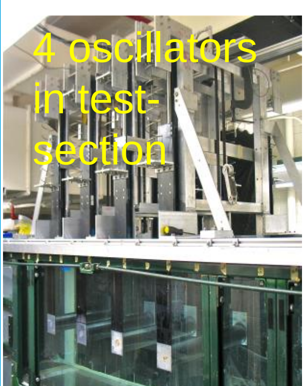
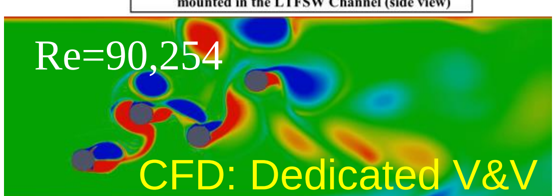
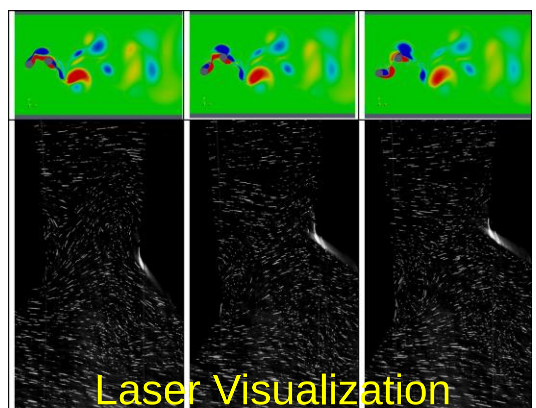


Figure 3. Two-oscillator Converter with V_{ck} mounted in the LTFSW Channel (side view)





Visulization of out-of-phase oscillations of two tandem cylinders using CFD and laser visulation; L/D=2.57, ζ =0.12, K=600N/m, Re=81,800.

Post-processing: HHT and EMD

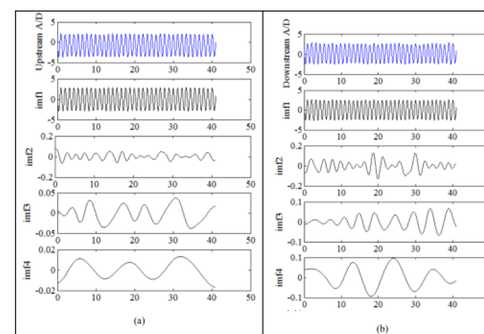


Figure 2. EMD of upstream (a) and downstream (b) cylinders at U=1.00m/s (Galloping) and L/D=2.57. The amplitude of imf2 (interactions) is around 0.02~0.07D for the upstream and 0.05~0.15D for the downstream cylinder.

Technical Objective #2: Build/test a full-scale *Oscylator-4* in the St. Clair River

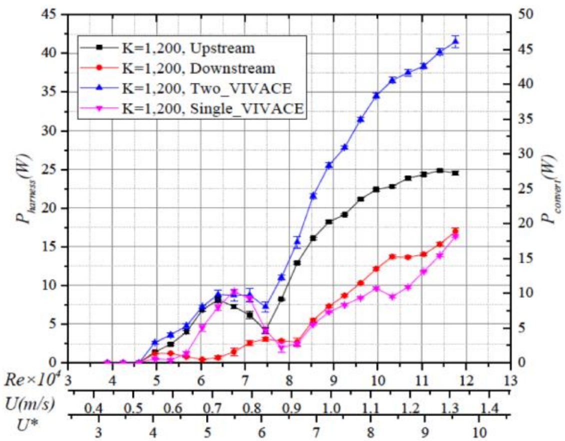
Figure 13: St. Clair River, Port Huron, MI Installation Site (Lake Huron to North)

Figure 14: Installation Location, Port Huron, MI

Excellent relations with

- Community
- Port Huron business development office
- BPAC (Binational Public Advisory Council)
- Local business (Dunn Paper, access to river)
- Local community loved the project
- Native American 1st Nation asked us to look into deploying in their waters

- Synergistic FIM, like fish in schools, increased harnessed power 2.7-7.5 times.
- Volume reduced by an order of magnitude as cylinder gap is optimal at 0.5•D rather than 10•D-20•D needed for wake diffusion.
- *Oscylator-4* has become a real 3-Dimensioanl energy converter due to compact cylinder formation in synergistic FIM.
- Power-to-Volume 400W/m³ at 1.3m/s (wind farms at 12m/s 0.01W/m³)



U_{flow} [m/s]	Converted Power [Watts]				
	1st Cyl.	2nd Cyl.	Synergy	Isolated	Ratio
0.90	12	3	15	2.0	7.5
1.00	20	8.5	28.8	7.5	3.84
1.10	24	12.5	36.5	10.0	3.65
1.23	27	16.0	43.0	13.0	3.31
1.28	27	17.0	44.0	15.5	2.84
1.32	27.5	18.5	46.0	18	2.56

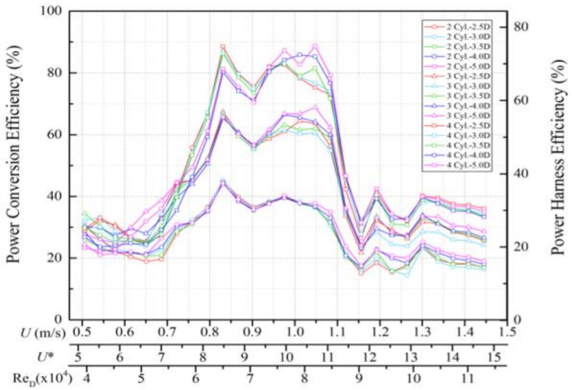


Figure 10. 2-3-4 cylinders harness & conversion efficiencies; *K*=745N/m, *m**=1.685, variable spacing. Efficiencies reach 88% off Betz [14].

Figure 9. Power of Two Cylinders in Synergy vs. an Isolated Cylinder; *k*=1,200N/m, $\zeta_{harness}$=0.24. MRELab model

2. Accomplishments and Progress

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- All permits acquired for 3-month deployment in the St. Clair River
- In field-tests, *Oscylator-4* operated for three months at ~2.3kt
- Durability in the marine environment was proven for three months in spite of some subsystem failures
- Fish observed with underwater camera were not disturbed
- LCOE projections based on actual costs (burdened by extremely high and unexpected costs of deployment/retrieval, which would not be present in a commercial deployment)
  - 3m/s: ¢15kWh-¢7kWh • 2.18m/s: ¢39kWh-¢20kWh • 1.65m/s: ¢90kWh-¢44kWh
- Based on actual cost and performance, expected reduction is to 0.05$/kWh

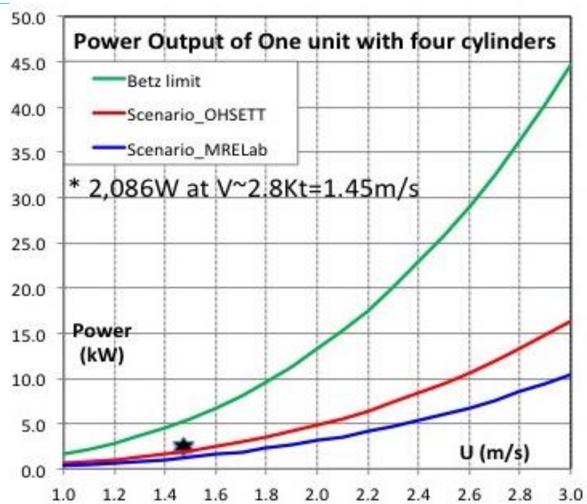

Figure 5. MHK Power

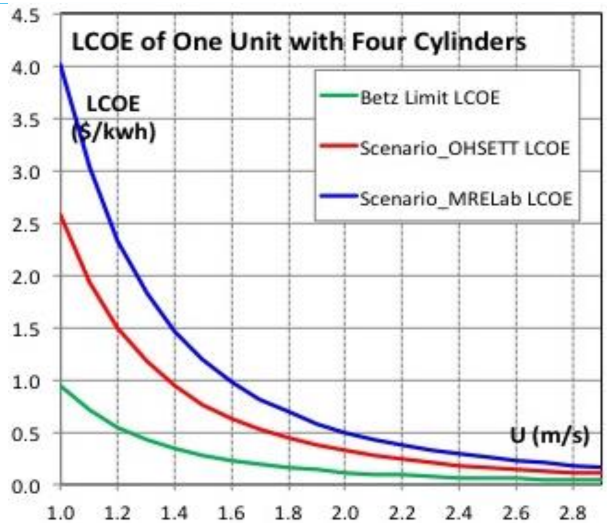

Figure 6. LCOE

Three scale tests: MRELab, OHMSETT, *River field-data; Betz

Data available for next step:

- Design for low cost in fabrication, deployment, maintenance
- Reach ¢15/kWh at lower flow speed (presently at 2.18m/s=4.24kt)
- Reconcile efficiency and power optima

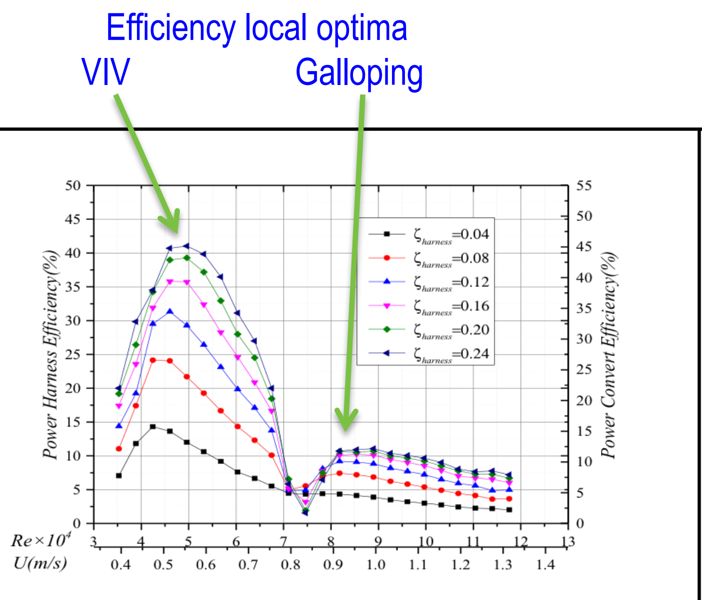

Figure 7. Single-cylinder harness & conversion efficiencies; K=600N/m, m^*=1.685, various $\zeta_{harness}$.

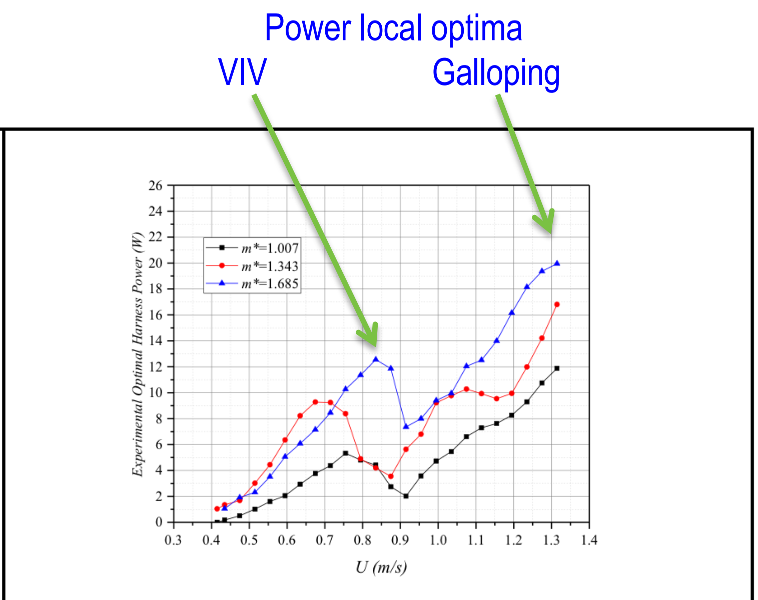

Figure 8. Power envelop for three mass ration values: m*=1.007, m*=1.343 and m*=1.685

3. Project Plan & Schedule

- Initiation Date: December 16, 2014
- Planned Completion Date: April 30, 2017
- Original installation date in 2015 could not be made due to delays in getting the necessary permits (8 months compared to three months in previous field-tests)
- Vortex Hydro Energy (VHE) had a successful project status review in 2016 prior to installing the device in the St. Clair River.


Deployment – UW camera view (6/24/2016)

UW camera view (6/30/2016)

3. Project Budget

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Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$443.230k	$63.029k	$460.897k	$89.841k

- There were no major variations in the project budget.
  - The cost of installation was higher than expected due to the increased weight of the *Oscylator-4.*
  - This extra cost was made up elsewhere in the project.
- $1.057M of $1.189M (90%) of funds has been spent
- In addition to DOE, VHE has received funds from the state of Michigan and a private investor.

4. Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- Partner: University of Michigan, Marine Renewable Energy Laboratory
- Collaborator: U.S. DOE, Wind and Water Power Technologies Office, Golden Field Office
- Subcontractors: Malcolm Marine, divers, fabricators

Communications and Technology Transfer:

- 44,942 website views since Apr 2013
- 16,844 YouTube video views (over 100,000 total)
- Nine Journal publications (Renewable Energy, Applied Energy, J. of Fluids and Structures, Ocean Engineering, JOMAE)
- 11 Conference papers (METS-2016, OMAE-2015, OMAE-2017)
- Topic sessions on VIVACE OMAE-2017
- Over 1,000 citations from around the world
- A chapter in the new Ocean Engineering Handbook by Springer
- At the University of Michigan main webpage (Oct. 31-Nov. 6, 2016)
- Statewide television, Fox-Sports for one week (Dec. 4-10, 2016)

5. Next Steps and Future Research

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FY17/Current research:

- Three-cylinder synergistic FIMs
- Parameters: velocity, spacing, stiffness, mass ratio, damping
- Objective: maximize MHK energy efficiency
  - Presently, energy capture with four cylinders is 88% of the Betz limit
- Barriers: - Understanding interaction between shear layers/vortex streets/bodies in FIM
  - Number of parameters
- Deliverable: Power curves for three cylinders in parametric form (April 2017)

Proposed future research:

- Understand multi-body FIM synergy: shear-layers/wakes/bodies
- Confirm with four cylinder synergistic FIMs
- Design to: Reconcile power with efficiency optima
  Minimize deployment and repair costs
  Reach ¢15/kWh at lower flow speed (presently at 4.24kt)