# Using Natural Instabilities in Fluid-Structure Interaction and Fish-Bioinspired Passive Control to Harness Hydrokinetic Energy

(VIVACE: a no-blade, no-rotor, hydrokinetic energy converter)

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VORTEX HYDRO POWER

# OUTLINE

I. **FSI** (Fluid Structure Interaction)

II. **UNDERLYING PHYSICS**
(Enhancing Instabilities and Fish Biomimetics)

III. **MHK** (Marine Hydrokinetic) **ENERGY**

IV. **CHALLENGES**

V. **DESIGN CONSIDERATIONS**

# I. Fluid Structure Interaction

- From hydrokinetic to mechanical
- Vortex Induced Vibrations
- Transition to galloping
- Galloping
- Coexistence of VIV and galloping
- Multiple bodies

**Objectives:** (1) Identify and understand multi-body FSI
(2) Identify high energy oscillatory patterns
(3) How to implement those in an MHK Converter (biggest challenge)

# I. FSI (1/13): 1. Smooth Cylinder VIV/FIO ($Re=10^5$)

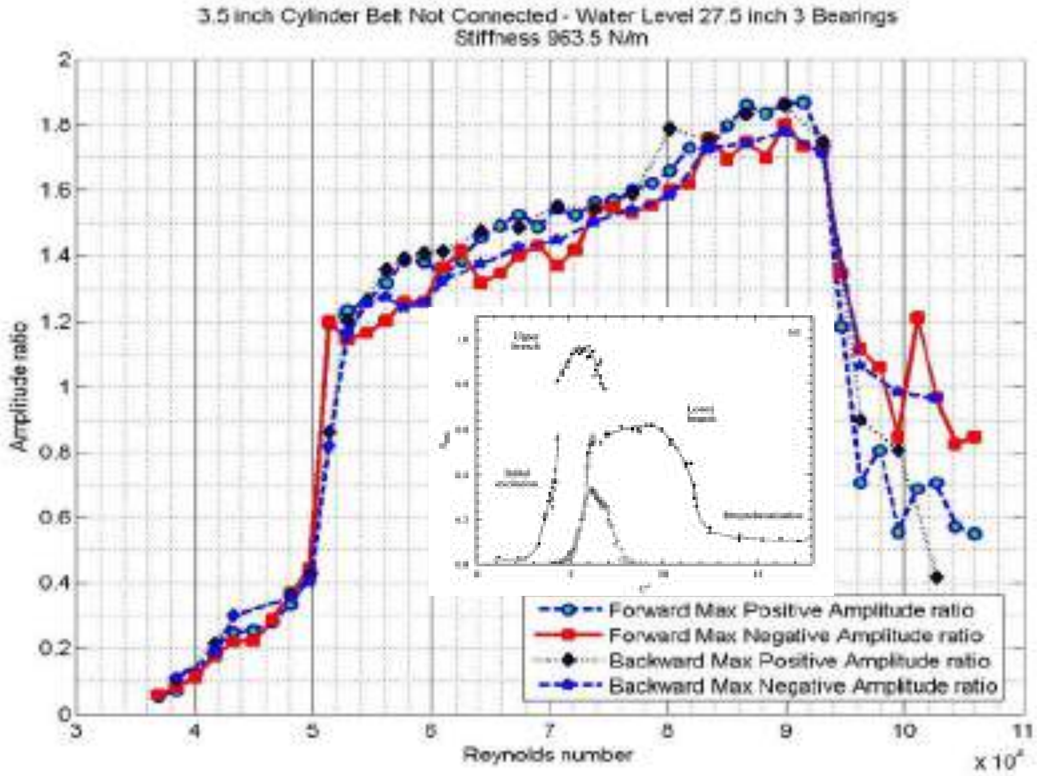
**Validation:** • Over 15-years of lab & field tests on 1-4 rigid cylinders, one-dof transverse oscillations

- Since 2005, 4 different models • Parameters: *K*, *m**, tip-effects, diameter, spacing, distance to boundaries, flow velocity
- TrSL3 flow regime: 20,000<*Re*<300,000

VIV Synchronization $U$=[0.56-1.05]m/s; $K$=2*518 N/m; $m^*$=1.45; (MRELab 2005)

**Observations:** • Broad range of synchronization

- Initial, upper, lower branches and desynchronization
- TrSL3[1] more powerful than TrSL2[2] (2,000<Re<20,000)
  - 3-10 times higher lift
  - Upper branch overtakes lower branch
  - Synchronization range expands
  - Amplitude nearly doubles



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[1] Raghavan, K., Bernitsas, M. M. (2010), "Experimental Investigation of Reynolds Number ..." Oc. Eng., V.38, No.5-6, April, pp.719-731.

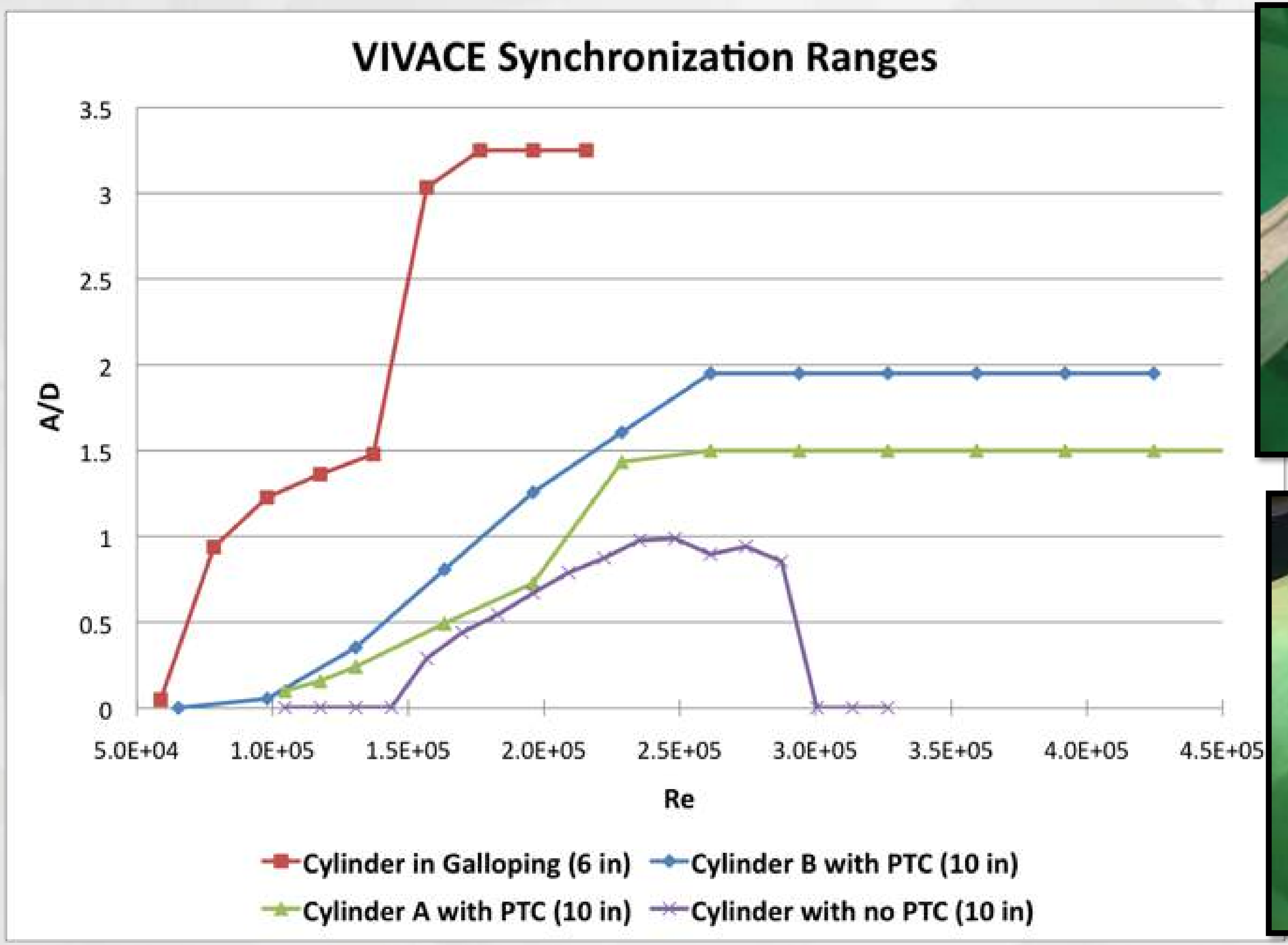
[2] Williamson & Govardhan. (2004)."Vortex-induced vibrations." An. Rev. of Fluid Mechanics, 36, 413-455.

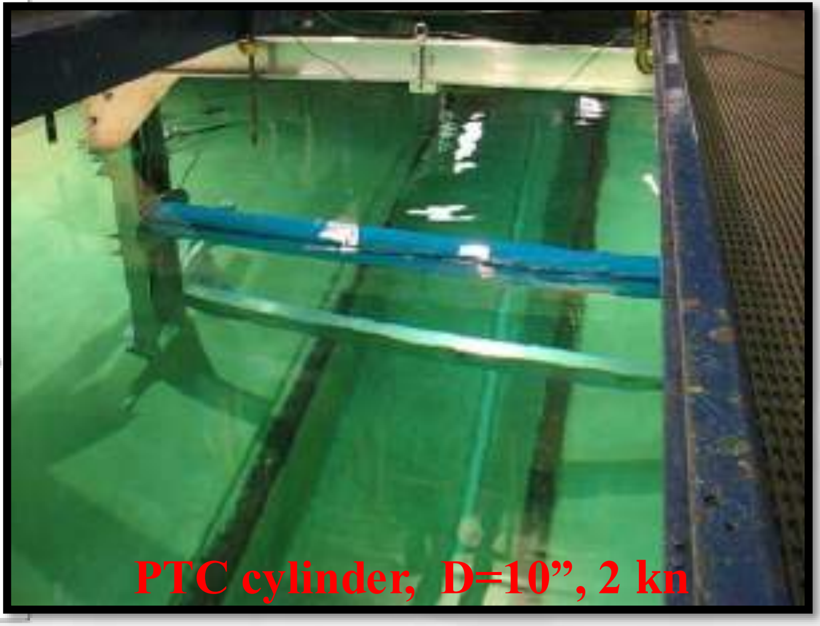
# I. FSI (2/13): 1. Smooth Cylinder VIV/FIO ($Re=2.07 \bullet 10^5$)

**Testing parameters:**

- Smooth cylinder
- $D$ = 10" ≅ 0.25m
- $L$ = 105" ≅ 2.70m
- V = 1.9 knots = 0.977m/s
- Re = $\frac{V \bullet D}{\nu} \cong 2.07 \bullet 10^5$

# I. FSI (3/13): 2. VIV Transition to Galloping (PTC cylinder in VIV/FIO)





# I. FSI (4/13): 3. Field Tests (PTC cylinder in VIV/FIO)

**Testing parameters:**

Variable flow speed

Ambient turbulence

- Smooth cylinder
- $D$ = 10" $\cong$ 0.25m
- $L$ = 105" $\cong$ 2.70m
- V = 2.3 knots = 0.977m/s
- Re = $\frac{V \bullet D}{\nu} \cong 2.507 \bullet 10^5$


The St. Clair River, Blue Water Bridge.


Gamma prototype underwater


Gamma being launched in St. Clair River

Underwater view of VIVACE cylinder

St. Clair river: Sept. 2012

# I. **FSI** (5/13): 4. Galloping

## Non-circular cylinders may gallop perpendicular to flow

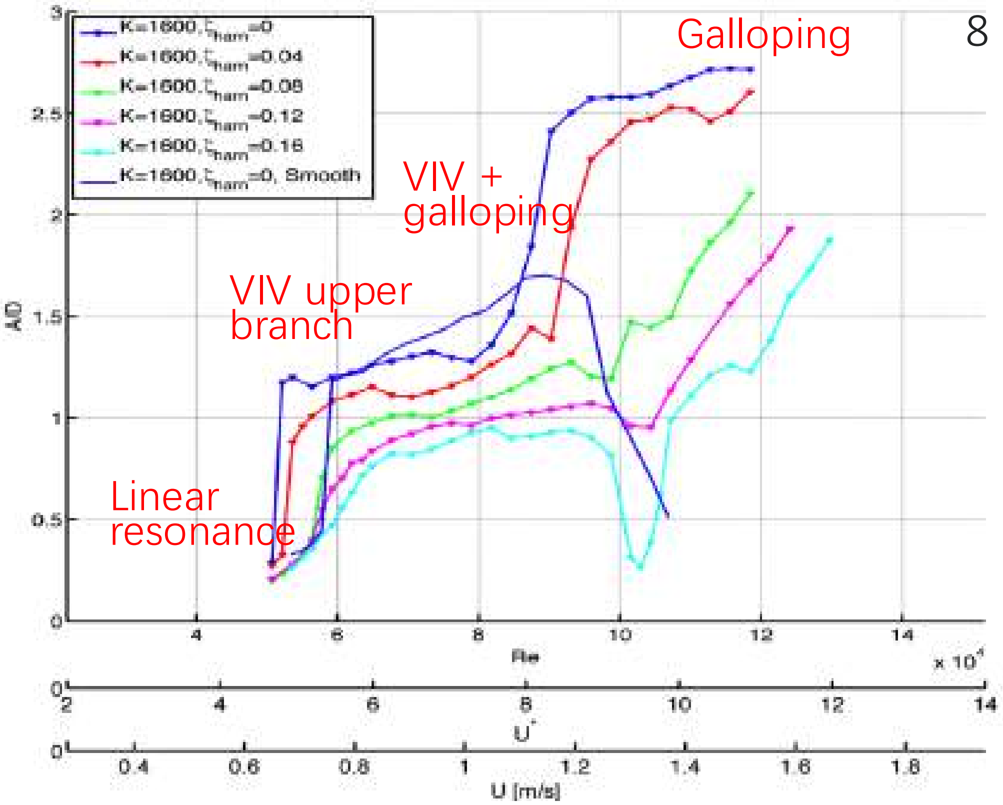
- VIV vs. galloping
  - Cause: in VIV, Vortex shedding
    in galloping, shear layer motion
  - *U*:* in galloping $U^*_g < U^*$[3]

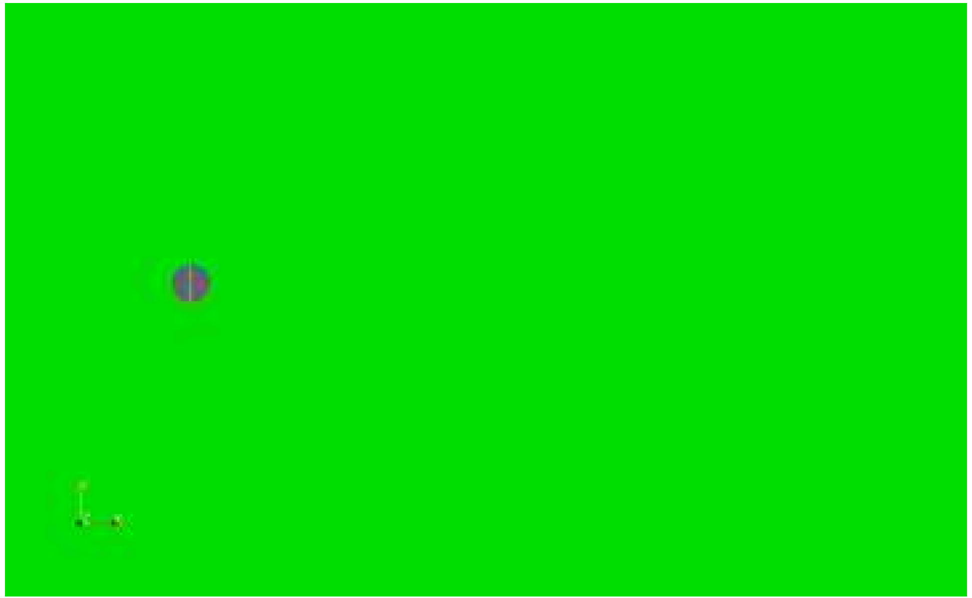
$$U_g = \frac{2c}{\rho D \frac{\partial c_y}{\partial \alpha}}$$

    in VIV ~4<*U**<~12
  - *A/D*: in galloping >> VIV and
    increases with U until failure
    in VIV it is self-limiting
  - $f_{osc}$ in galloping drops below $f_{n,vac}$
    in VIV increases above $f_{n,vac}$

- Transition VIV to galloping
  - Cause: gap in FIO
    coexistence of mechanisms

**Testing parameters:**
Variable flow speed, Ambient turbulence
D=6″, L=60″, ζ=0.03, k=500N/m, m*=1.68,
V= 1.16m/s (2.25kn), $Re = \frac{V \bullet D}{\nu} = 1.475 \bullet 10^5$





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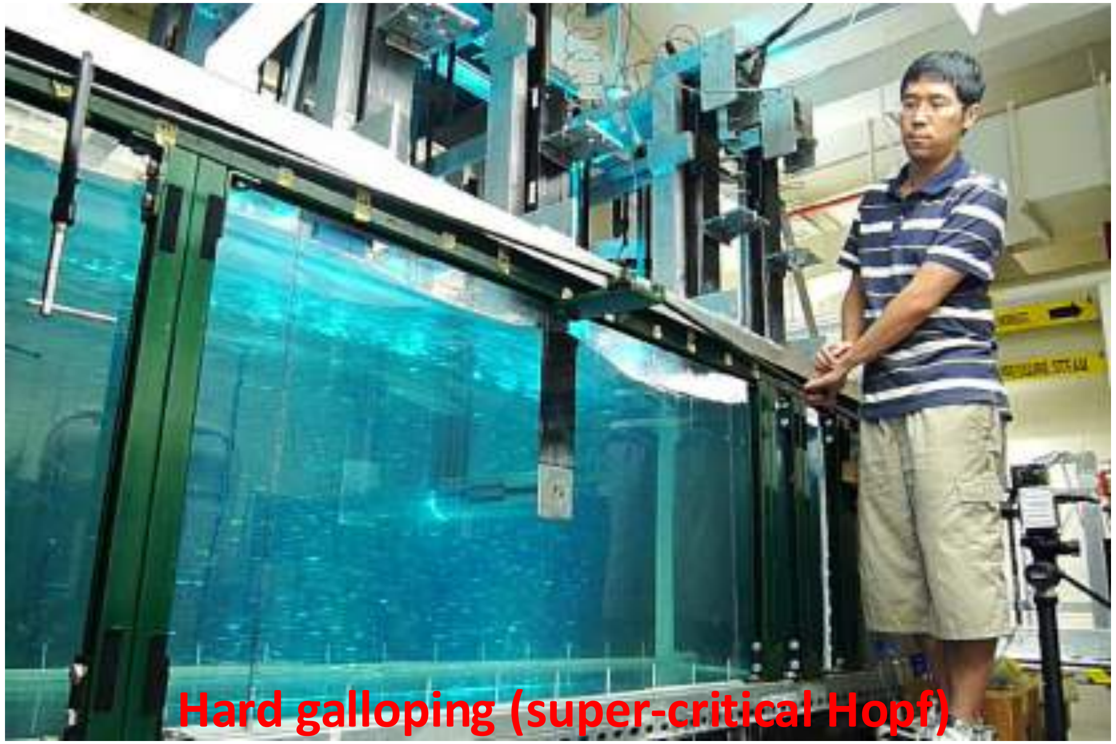
[3] Vortex Induced Vibration, Blevins 1990

# I. FSI (6/13): 5. Hard Galloping (PTC cylinder in VIV/FIO)



(1) [Soft] **galloping:** requires no initial push

(2) **Hard galloping:** requires threshold push

(3) **Wake galloping**: elastic cylinder in the wake of a fixed upstream cylinder. [F-O]

(4) **Proximity galloping:** flexibly-mounted upstream cylinder with another fixed cylinder placed in its wake. Spacing ≤ 2•*D*. Change in the shear layers of the upstream cylinder due to the downstream cylinder. [O-F]

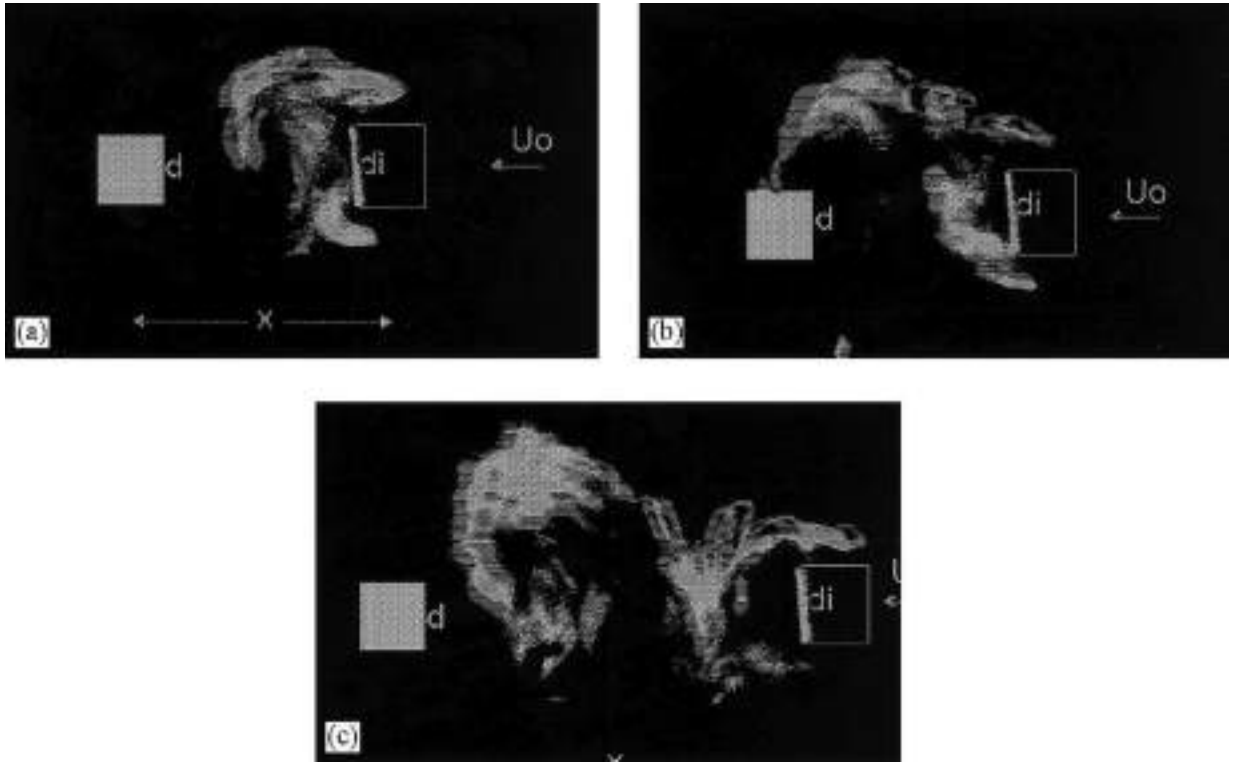
(5) **Interference galloping:** two elastic cylinders. C2C spacing ≤ 3•D. Flow direction reaches critical angle. Unlike classical galloping (where $dC_L/d\alpha$ is -ve) $dC_L/d\alpha$ is +ve. This is due to the negative hysteresis lag angle. [O-O]

# I. FSI (7/13): 6. Buffeting & 7. Flutter

Due to:

(a) Impingement of upstream vortices.

Amplitude increases with increasing velocity for buffeting; similar to galloping but more gradually.



(b) High turbulence in oncoming flow

Very similar to galloping in the amplitude-velocity trend (instability in airfoils).

It can be in the form of:

(a) 2-D torsion-plunge coupled instability

(b) 1-D stall flutter.

$$m\ddot{y} + 2m\zeta_y\omega_y\dot{y} + S_x\ddot{\theta} + k_y y = F'_y, \qquad (4\text{-}45)$$

$$J_\theta\ddot{\theta} + 2J_\theta\zeta_\theta\dot{\theta} + S_x\ddot{y} + k_\theta\theta = F'_\theta, \qquad (4\text{-}46)$$

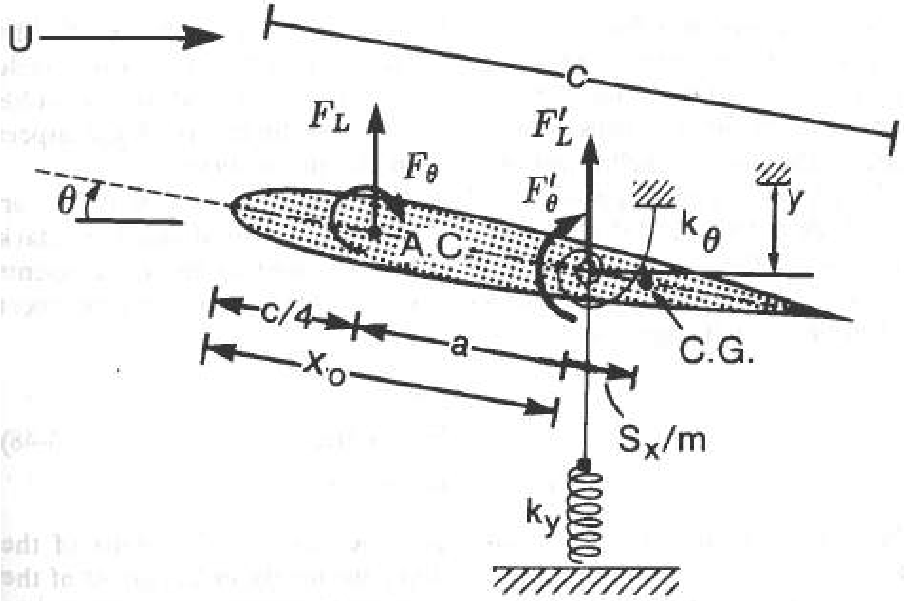


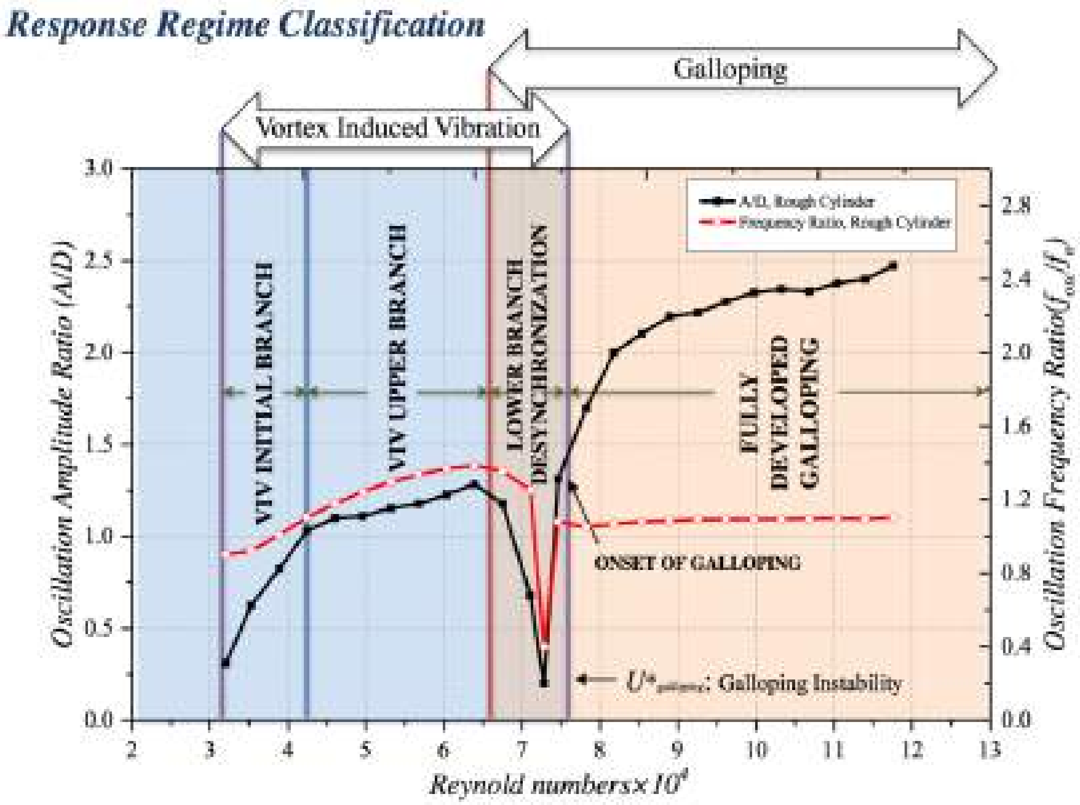
Fig. 4-16 Two-dimensional airfoil section supported by vertical and torsional springs. A.C. is the aerodynamic center and C.G. denotes the center of mass. [3. Blevins]

# I. FSI (8/13): 8. VIV and Galloping

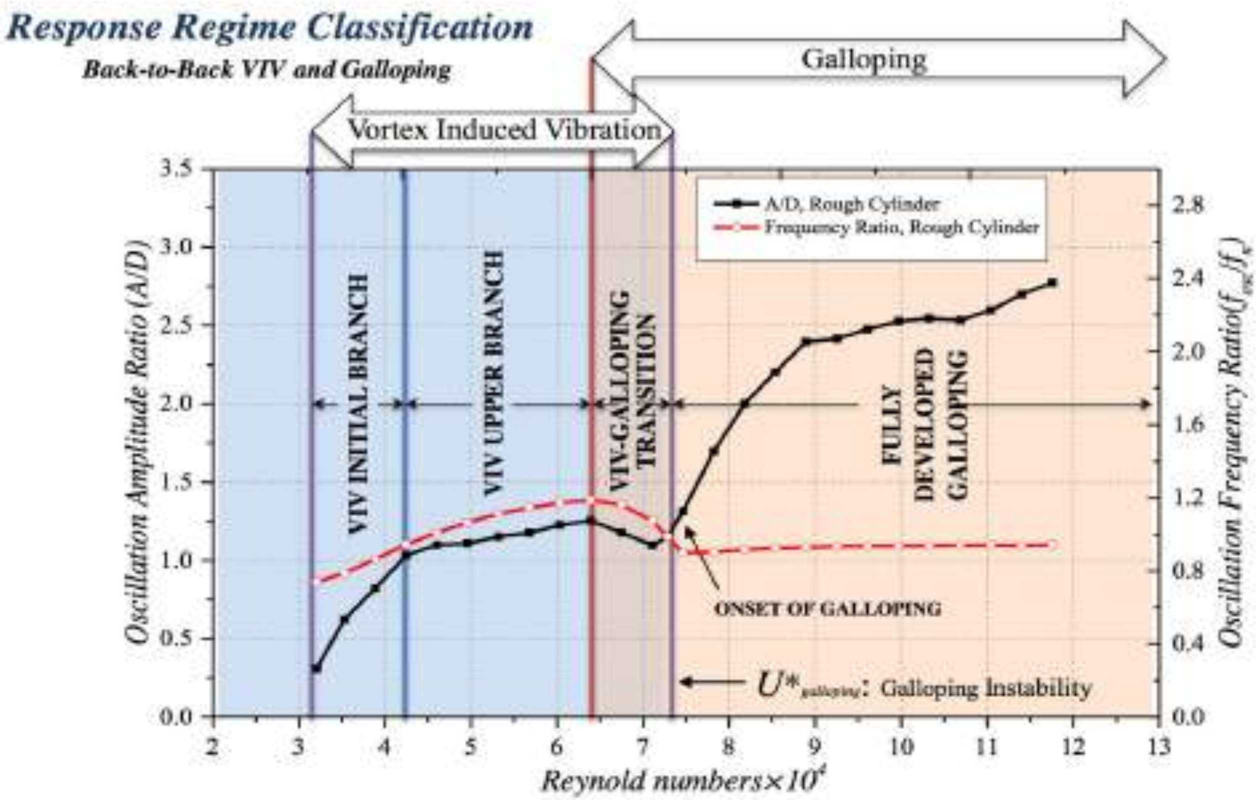
FIO { VIV
Galloping

- Galloping is an instability
- VIV is nonlinear resonance
- A smooth circular cylinder in a uniform flow cannot gallop.

## FIO branches for a single cylinder with distributed surface roughness to induce galloping



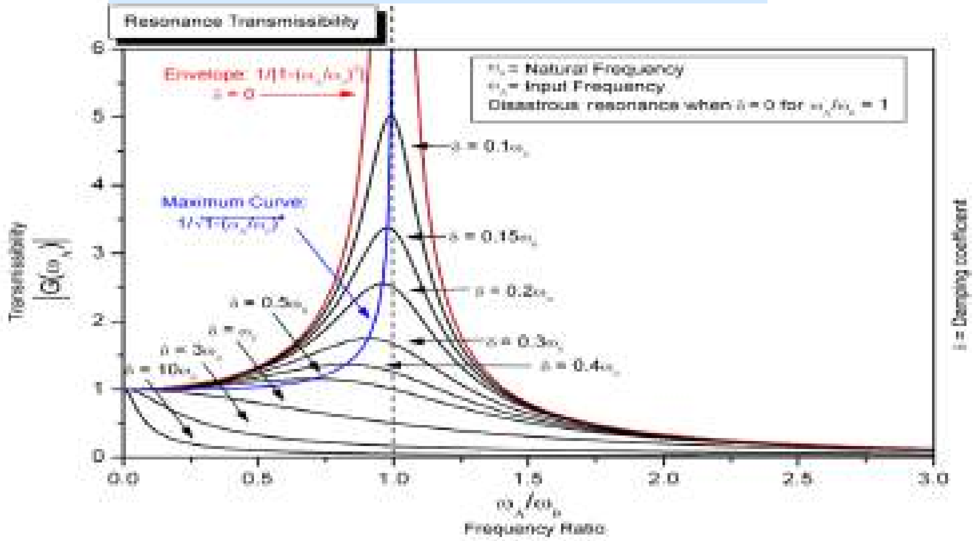
FIO regions with small overlap between VIV and galloping; $K$=400N/m, $\zeta$=0.12 [4. Sun et al. 2016]



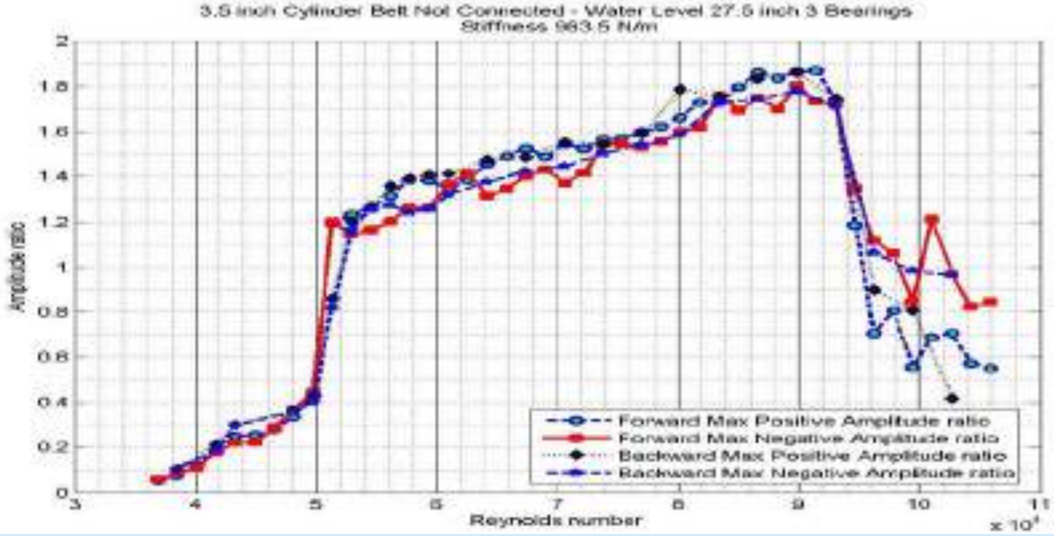
Flow Induced Motion regions with overlap of VIV and galloping; $K$=600N/, $\zeta$=0.04 [4. Sun et al. 2016]

# I. FSI (9/13): 9. Open - Ended RAO

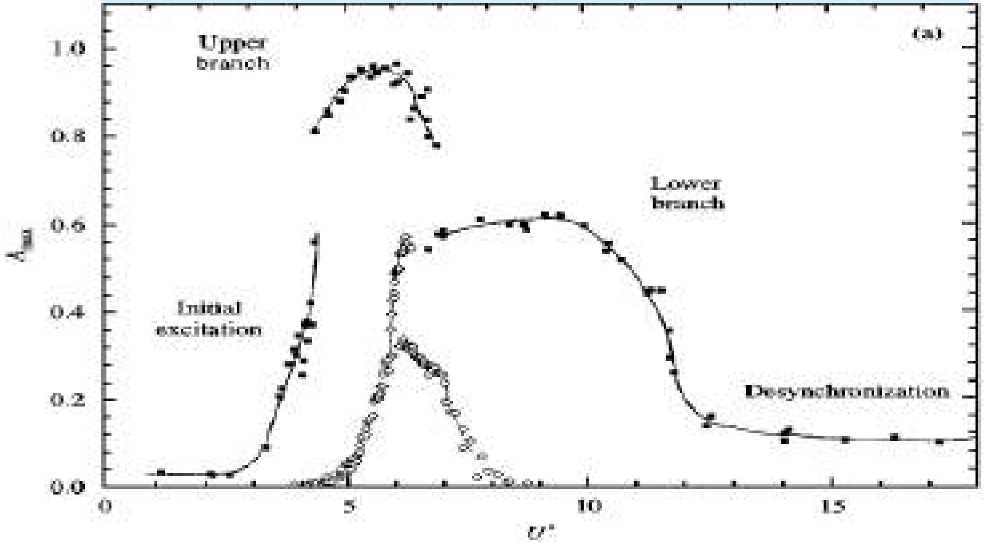
## Linear oscillator



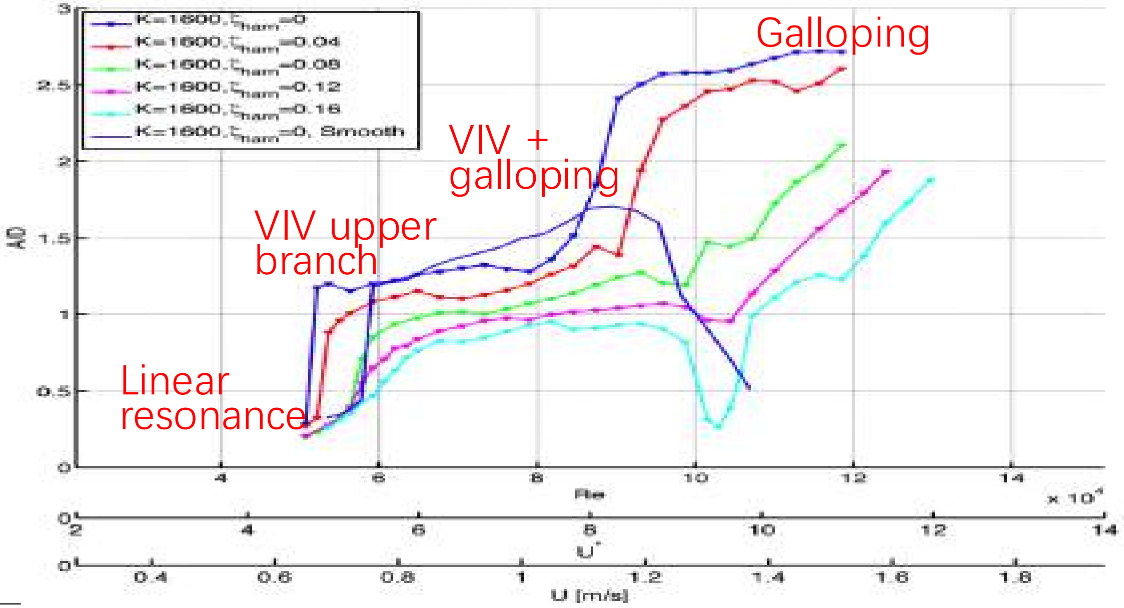
## VIVACE, VIV high-Re oscillator (TrSL3)



## VIV, low-Re oscillator (TrSL2)[2,5]



## VIVACE, VIV+galloping oscillator



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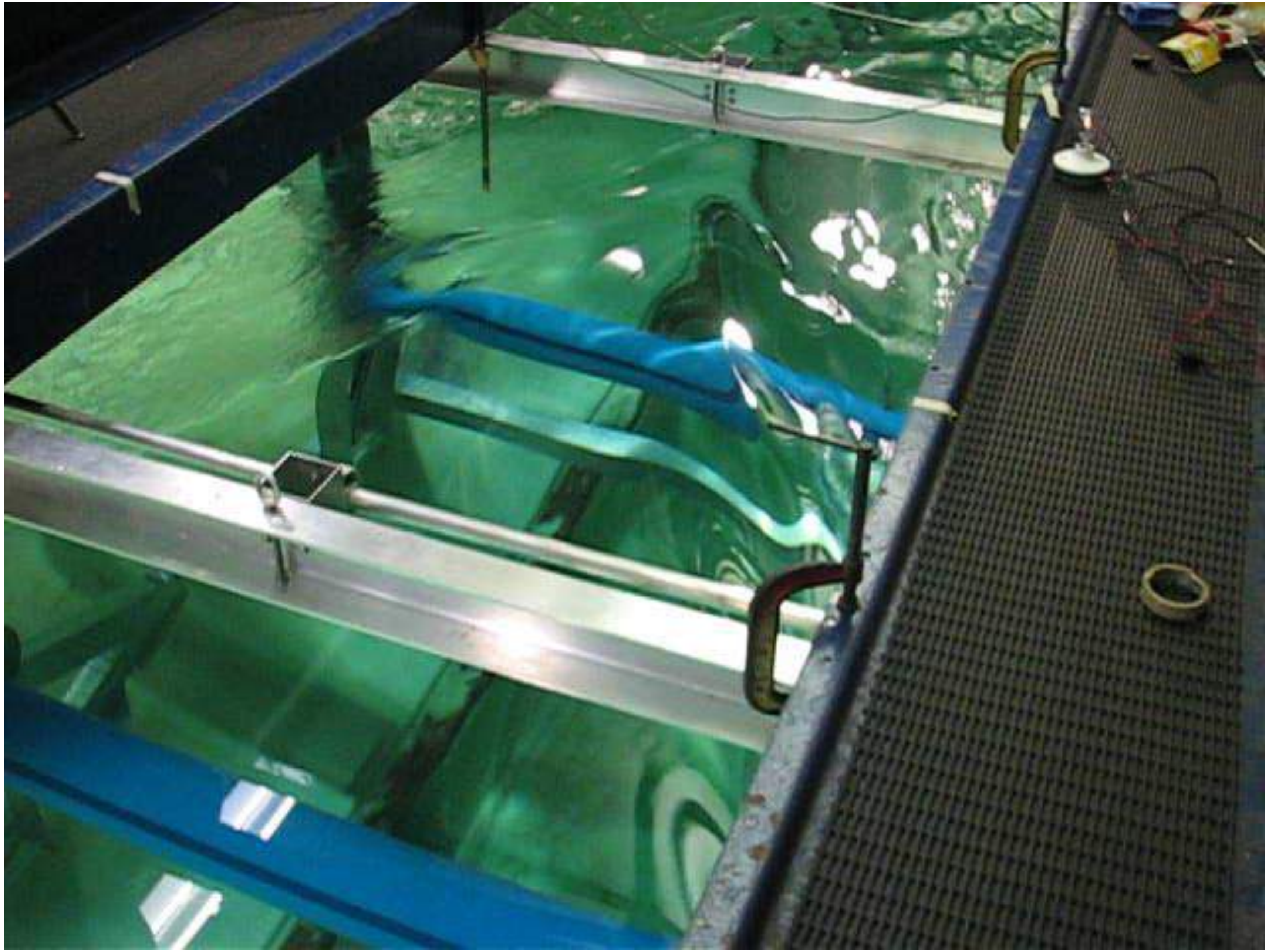
[5] Feng, 1968, “The measurement of vortex induced effects in flow past stationary and oscillating circular and D-section cylinders”, MS Thesis Univ. of British Columbia

# I. FSI (10/13): 10. Two PTC-Cylinders 2 knots



## Testing parameters:

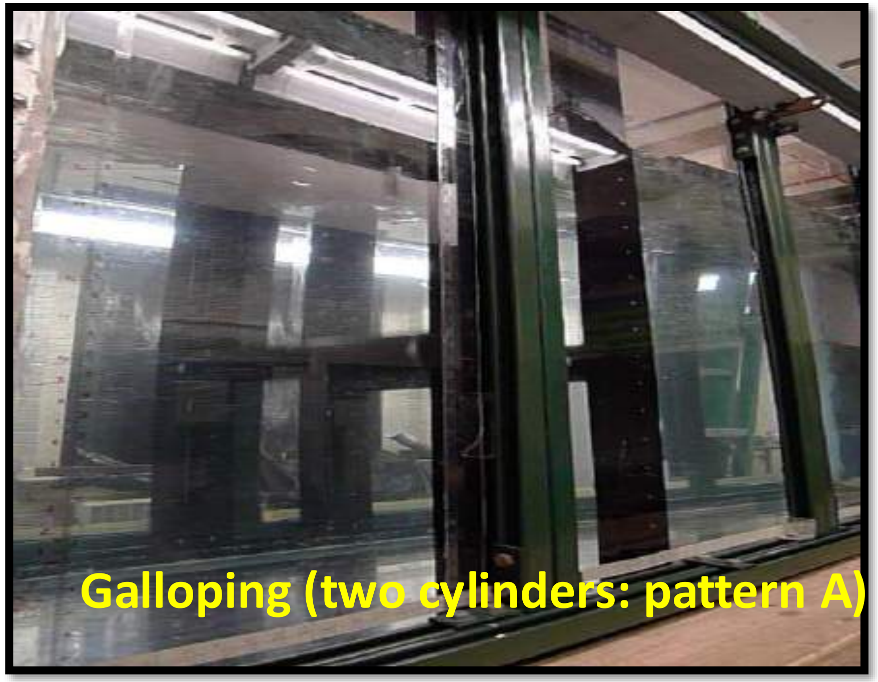
- PTC cylinders
- $D$ = 10" ≅ 0.25m
- $L$ = 105" ≅ 2.70m
- V = 1.9 knots = 0.977m/s
- Re = $\frac{V \bullet D}{\nu} \cong 2.07 \bullet 10^5$

Interference up to 20•*D* spacing

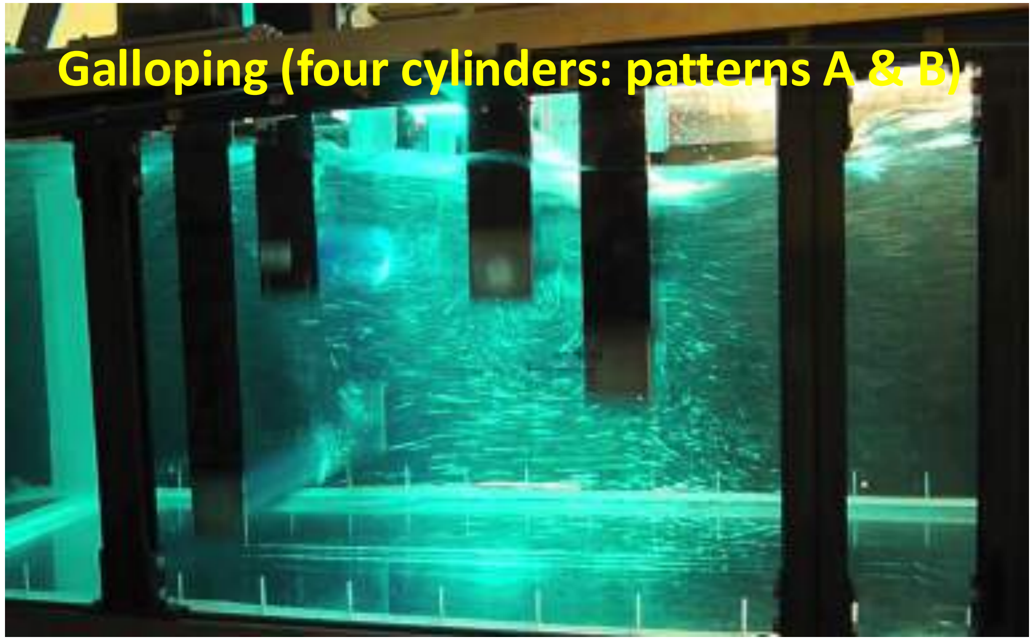
# I. FSI(11/13): 11. Multiple Cylinders

**Complexity: Interaction between**

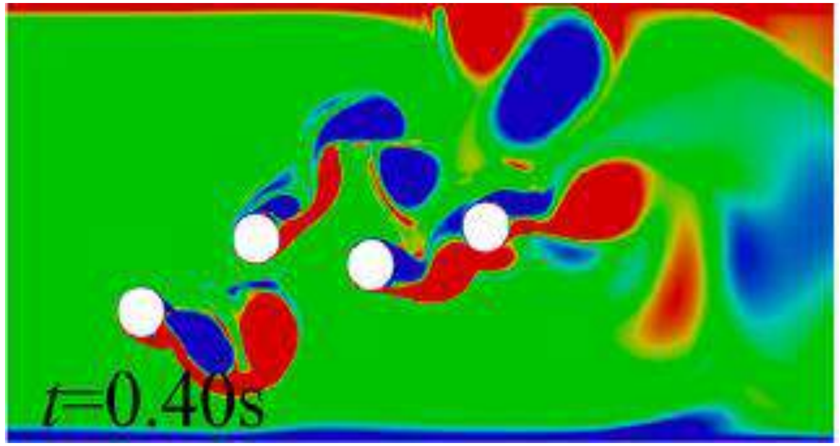
- Stagnation points • Boundary Layers • Separation points
- Shear layers • Roll up of shear layers • von Kármán vortices
- Vortical wakes • Oscillating bodies • Ambient vorticity
- Shielding effect • Vorticity coalescence/cancellation



Galloping (two cylinders: pattern A)



Galloping (four cylinders: patterns A & B)



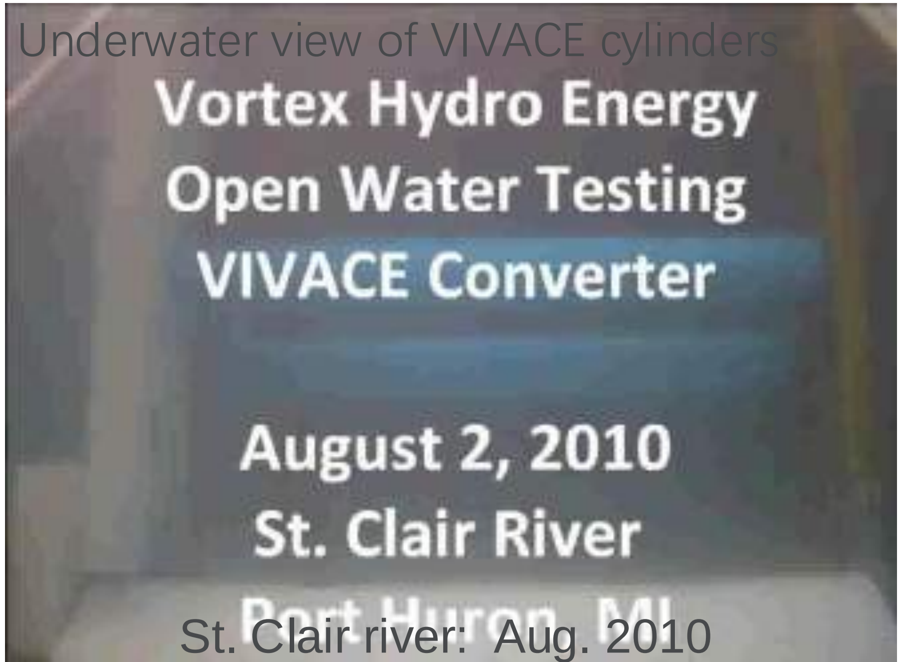
**Objective:** Each cylinder maintain high circulation for lift, in spite of shielding

# I. **FSI** (12/13): 12. Two-Cylinder Field-Tests


The St. Clair River, Blue Water Bridge.


Beta 1 Prototype at dock


Beta 1 being tested in St. Clair River


Underwater view of VIVACE cylinders

Vortex Hydro Energy
Open Water Testing
VIVACE Converter

August 2, 2010
St. Clair River
Port Huron, MI

St. Clair river: Aug. 2010

# I. FSI (13/13): 13. Multiple Bodies

TrSL3 flow regime： 20,000<*Re*<130,000 in the recirculating channel

## Three PTC cylinders

Large turbulence stimulation

## Four smooth cylinders

Center to Center distances:

1 to 2: 1.95 Diameters
2 to 3: 3.95 Diameters
3 to 4: 1.63 Diameters

Cylinder spacing robustness

**Conclusion:** Proximity is beneficial for high energy patterns. Find parameter ranges

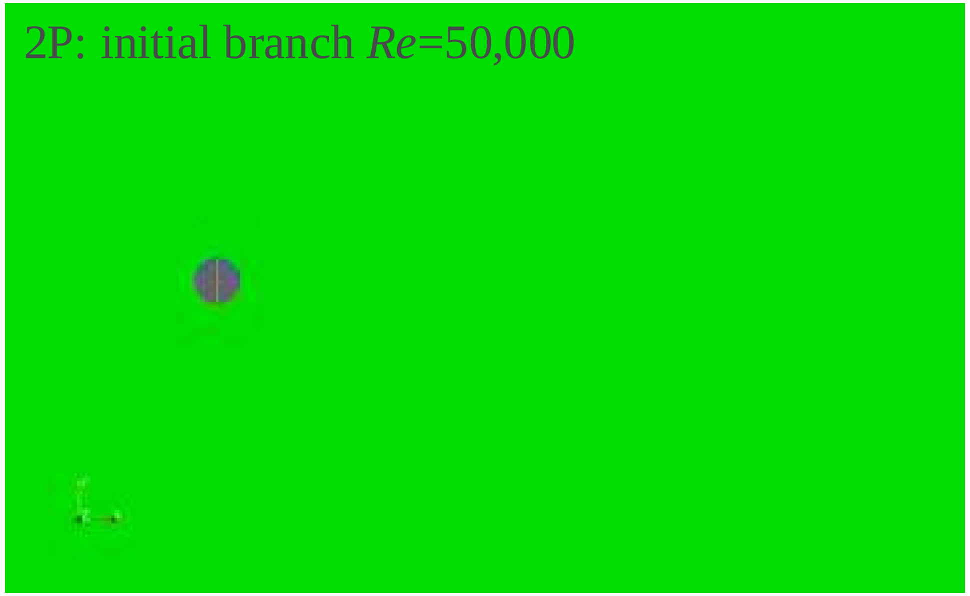
# II. Underlying Physics

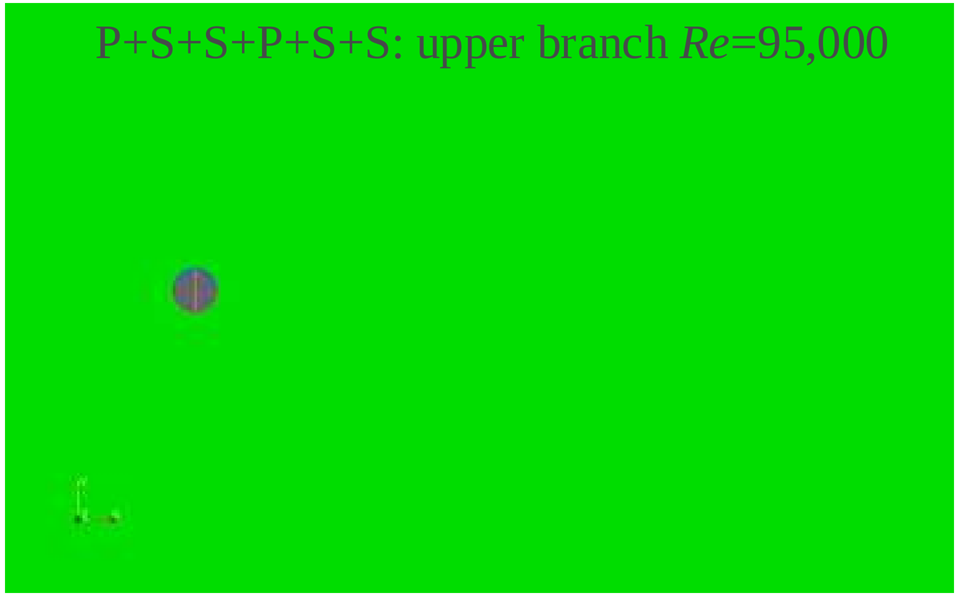
- VIV: Alternating vs. steady lift
- RAO: Design using turbulence stimulation
- VIV & Galloping: Oscillating using steady lift
- Multibody interactions: High response patterns
- Motivation: Fish-school dynamics w/o its complex kinematics
- Bifurcations: wrt velocity
- Bi-stabilities: wrt time
- Motion control: Presently good modeling not possible
- Implementation: Adaptive oscillator properties

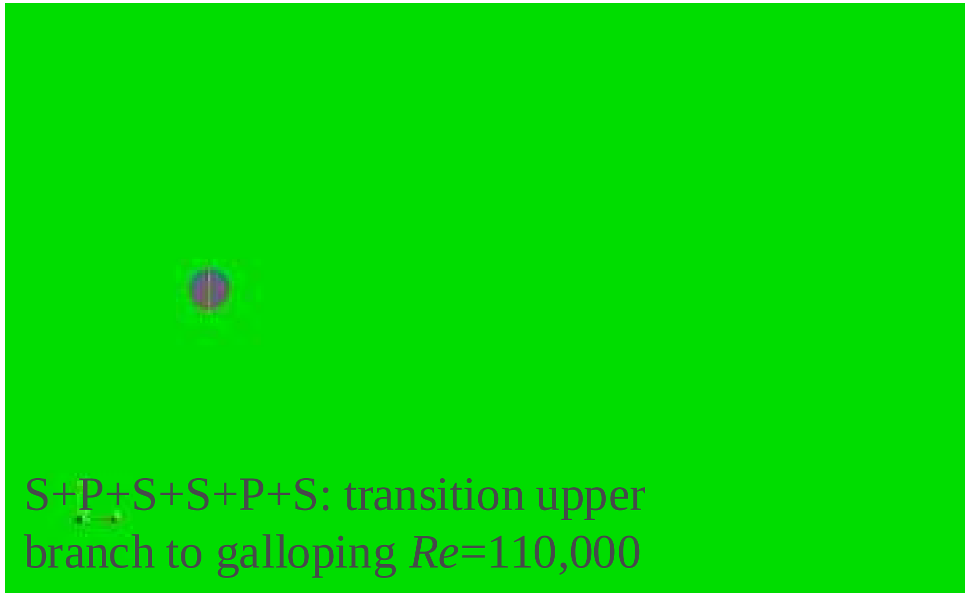
Extensive experimental database, good CFD, sufficient understanding
**Challenge:** How to implement results in an MHK Converter

# II. UNDERYLING PHYSICS (1/15): 1. Vortex Induced Vibrations

## Cylinder with PTC in VIV in TrSL3: 20,000<*Re*<300,000


2P: initial branch *Re*=50,000

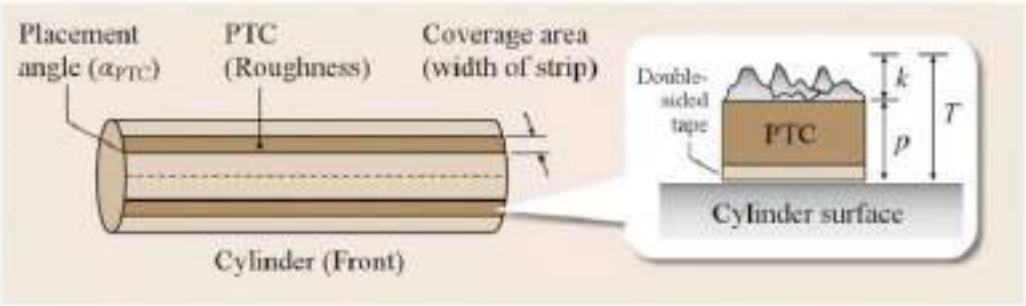

P+S+S+P+S+S: upper branch *Re*=95,000


S+P+S+S+P+S: transition upper branch to galloping *Re*=110,000

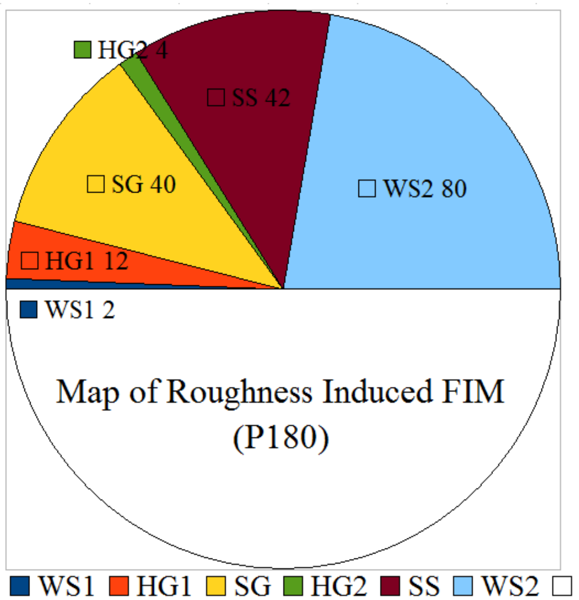

2P+8S: galloping *Re*=130,000

# 2. RAO: Design by Turbulence Stimulation

## PTC-to-FIM Map[6] (Turbulence stimulation thickness ≈ Boundary Layer thickness)



0.5" width, P180 roughness



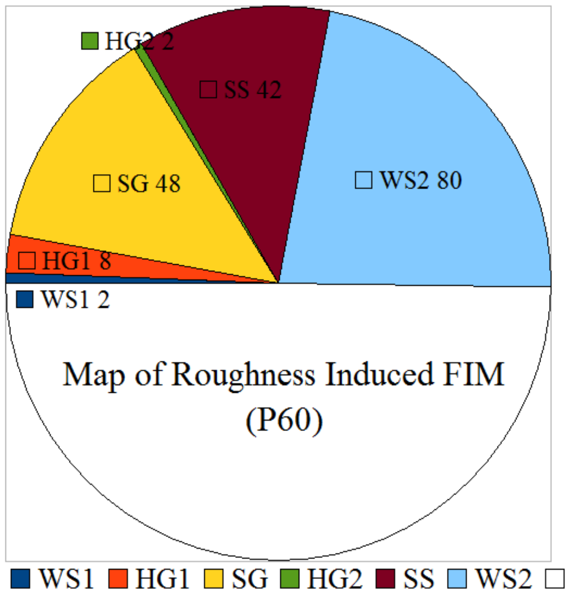
### 6 Zones

WS1/2: Weak Suppression
SS: Strong Suppression
HG1/2: Hard Galloping
SG: Soft Galloping

### Zone – Dominance[35]

1st Strong Suppression
2nd Galloping

0.5" width, P60: Increased SG; Decreased HG1/2



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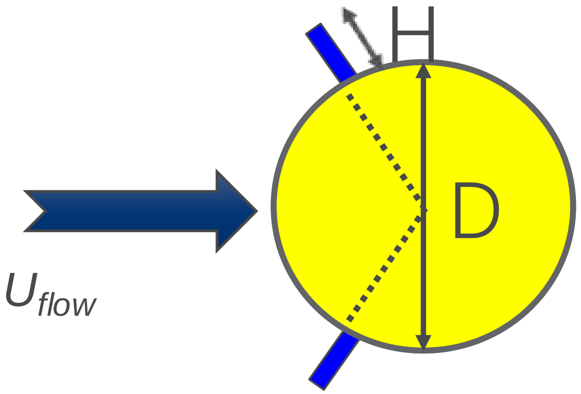
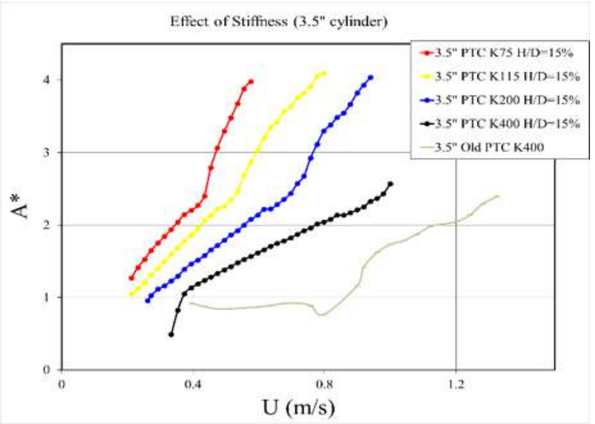
[6] Park, H. R., Kim, E.S., Bernitsas, M. M., “Sensitivity to Zone Covering of the Map of Passive Turbulence Control to Flow-Induced Motions for a Circular Cylinder at 30,000<Re<120,000”, J of Offshore Mechanics and Arctic Engineering, 2017; 139 (2): 021802-021802-6

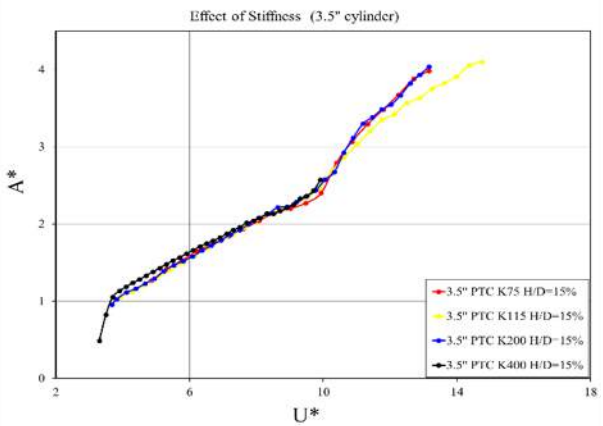
[7] Park, H. R., R. A. Kumar, Bernitsas, M. M., “Enhancement of Flow Induced Motions of Rigid Circular Cylinder on Springs by Localized Surface Roughness at 3×104≤Re≤ 1.2×105”, Ocean Engineering, Vol. 72, 1 November 2013, Pages 403-415.

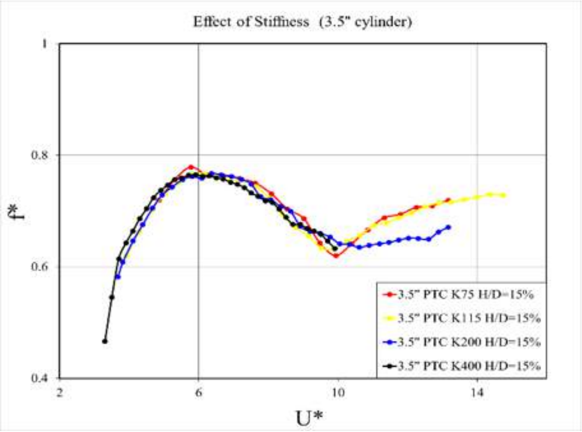
# II. UNDERYLING PHYSICS (3/15): 2. RAO: Onset of FIO; VIV vs. galloping

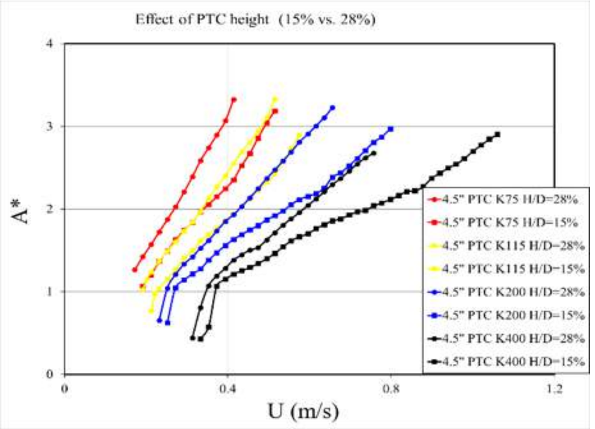
- …… but **not** earlier than the onset of VIV

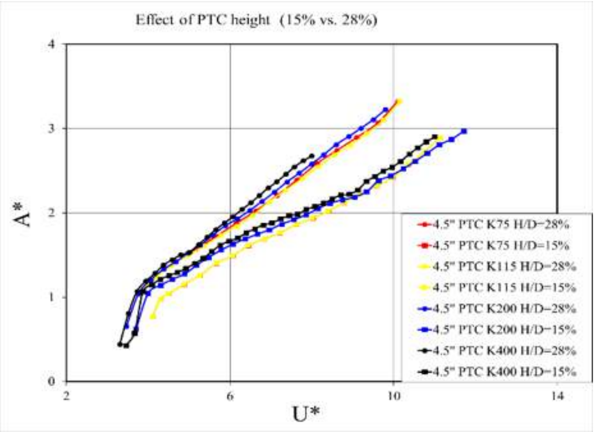


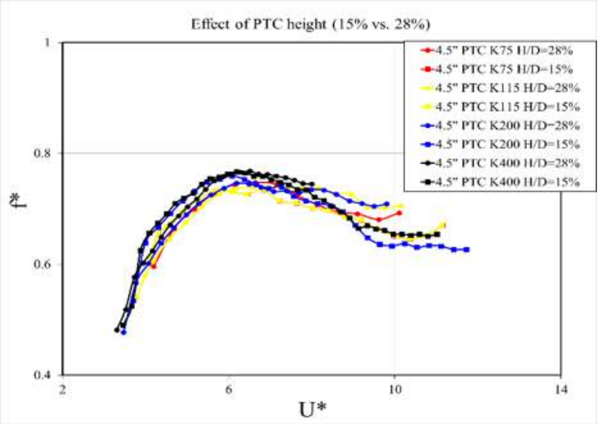












***D***= 3.5" & 4.5"

***H/D***= 15% & 28%

***K***= 75, 115, 200, 400 N/m

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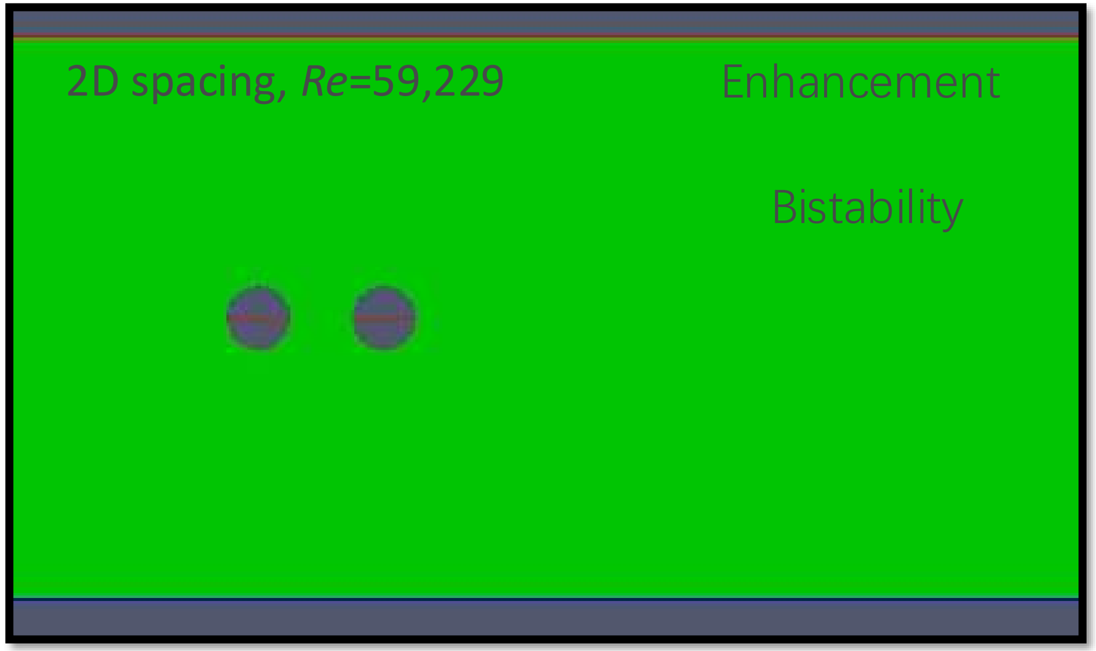
[8] Hongrae Park, Andreas Mentzelopoulos, Michael M. Bernitsas, "Hydrokinetic Energy Harnessing from Slow Currents using Flow Induced Oscillations", Ocean Engineering, (2020)

# II. UNDERYLING PHYSICS (4/15): 3. VIV & Galloping

## Two cylinders with PTC in VIV/galloping in TrSL3: 20,000<*Re*<300,000

2D spacing, *Re*=30,000

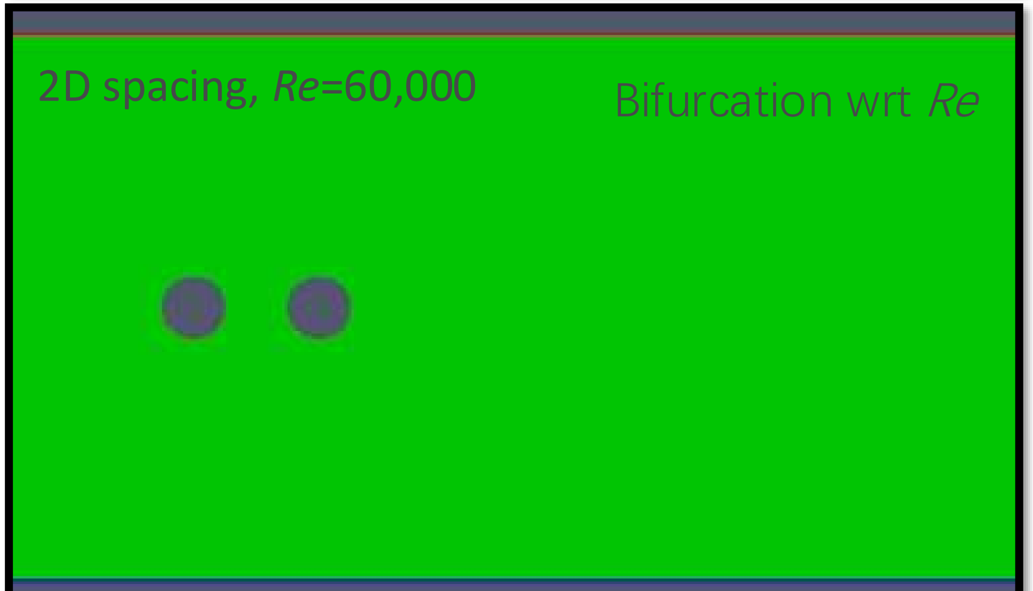
Suppression



2D spacing, *Re*=59,229

Enhancement

Bistability



2D spacing, *Re*=60,000

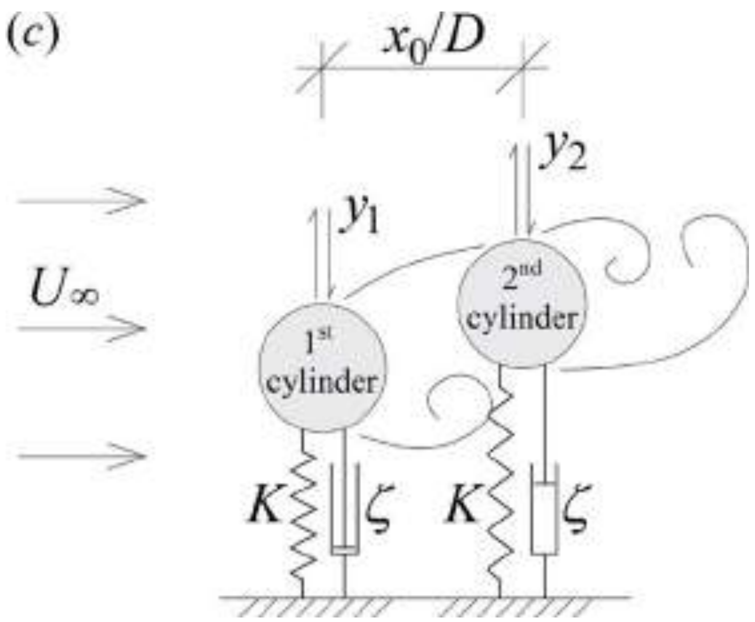
Bifurcation wrt *Re*

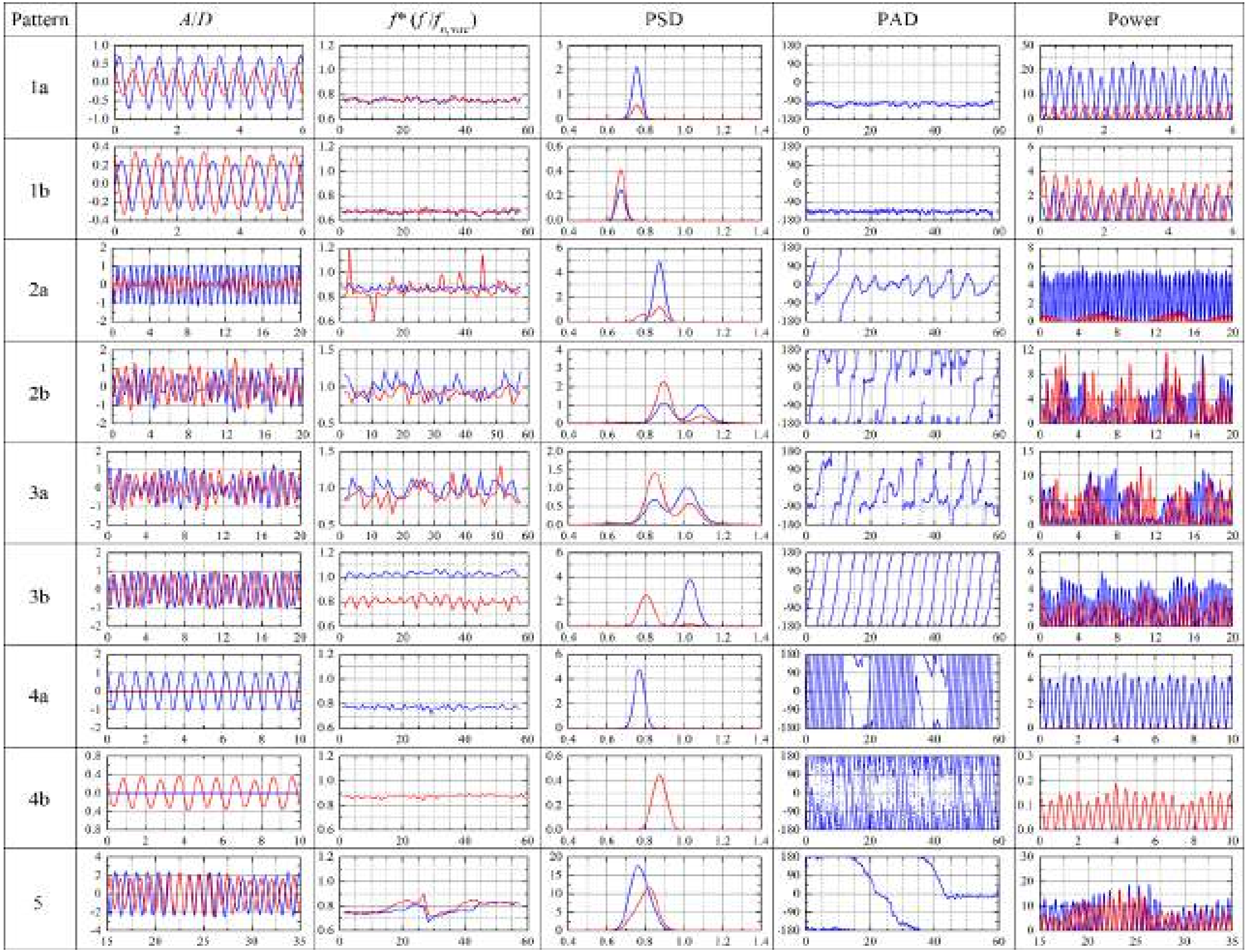
2D spacing, *Re*=90,000

Galloping

# II. UNDERYLING PHYSICS (5/15): 4. Bi-Stabilities

Two PTC cylinders. Summary of the dynamic characteristics of all identified patterns





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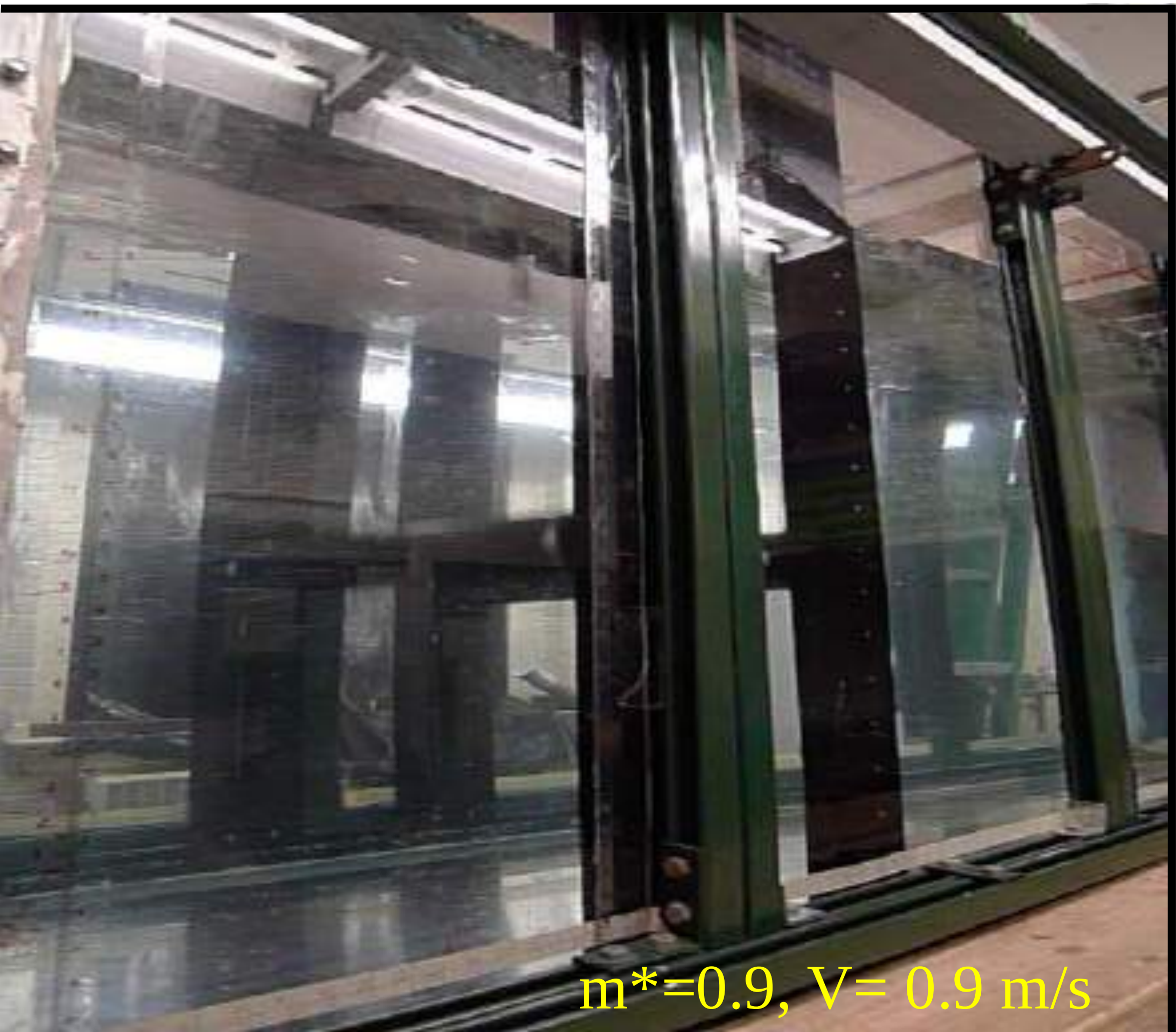
[9] W Yuan, H Sun, H Li, M M Bernitsas, “Flow-Induced Oscillation Patterns for Two Tandem Cylinders with Variable Stiffness and Damping”, Ocean Engineering, Vol. 218, Dec 2020

# II. UNDERYLING PHYSICS (6/15): 5. Synergy between two cylinders

**Can cylinders in close formation be in FIO and harness MHK energy efficiently?**

TrSL3 flow regime： 20,000<*Re*<130,000

| Mass Ratio | Aspect Ratio | Max. Oscillatory Amplitude | Longitudinal Spacing | Damping Ratio $\zeta$ |
|---|---|---|---|---|
| $0.634 \leqslant m^* \leqslant 2.00$ | $L/D = 10.07$ | $A_{max}/D_{3.5''} = 5.5$ | $1.429 \leqslant d/D_{3.5''} \leqslant 6.0$ | $0.02 \leqslant \zeta \leqslant 0.26$ |



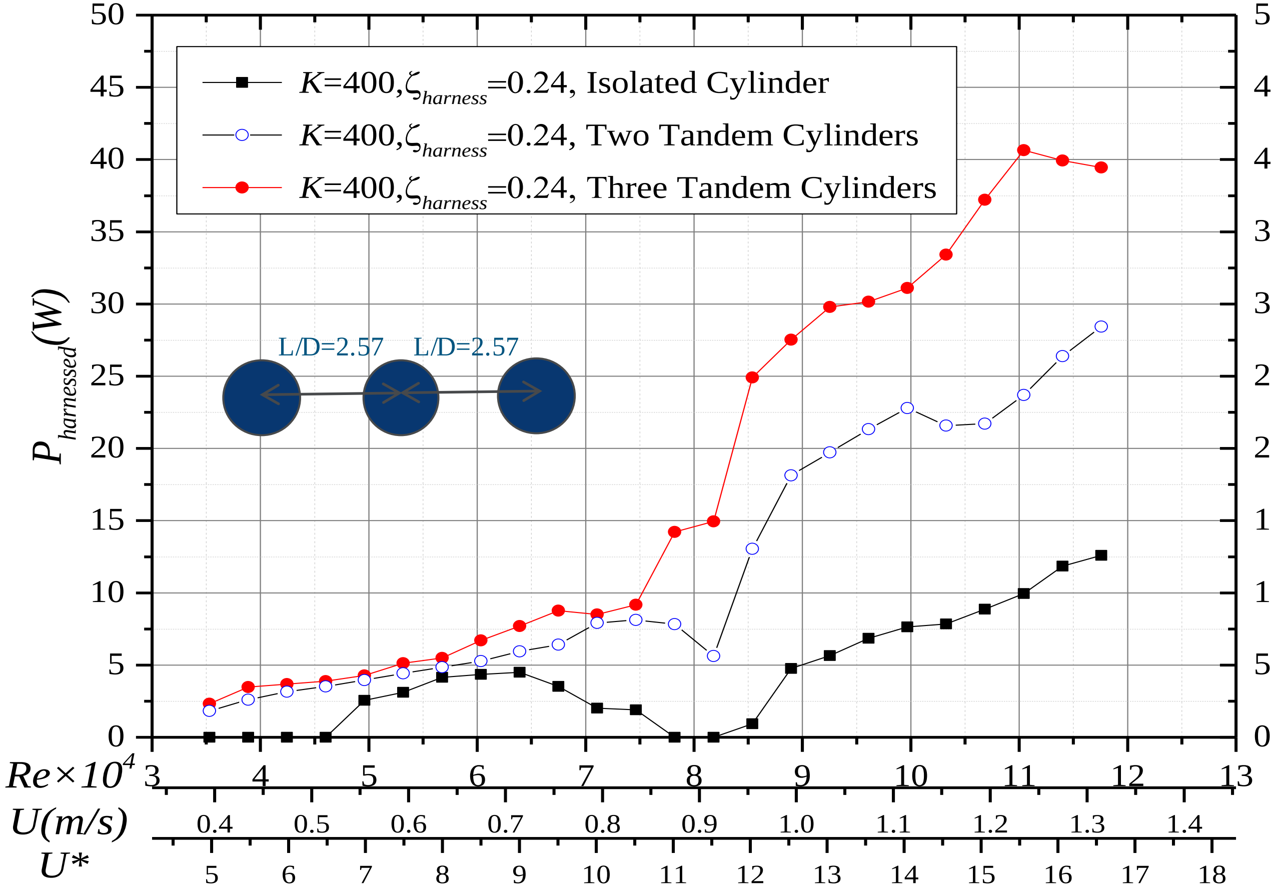
$m^*=0.9$, V= 0.9 m/s

$m^*=1.67$, V= 1.3 m/s

# 5. Synergy between three cylinders

At **L/D=2.57,** *K*=400N/m, $\zeta_{harness}$ = 0.24: Best of all (*K*, $\zeta_{harness}$) tested

In galloping, three cylinders generate **3.4-5.3** times the power of a single cylinder



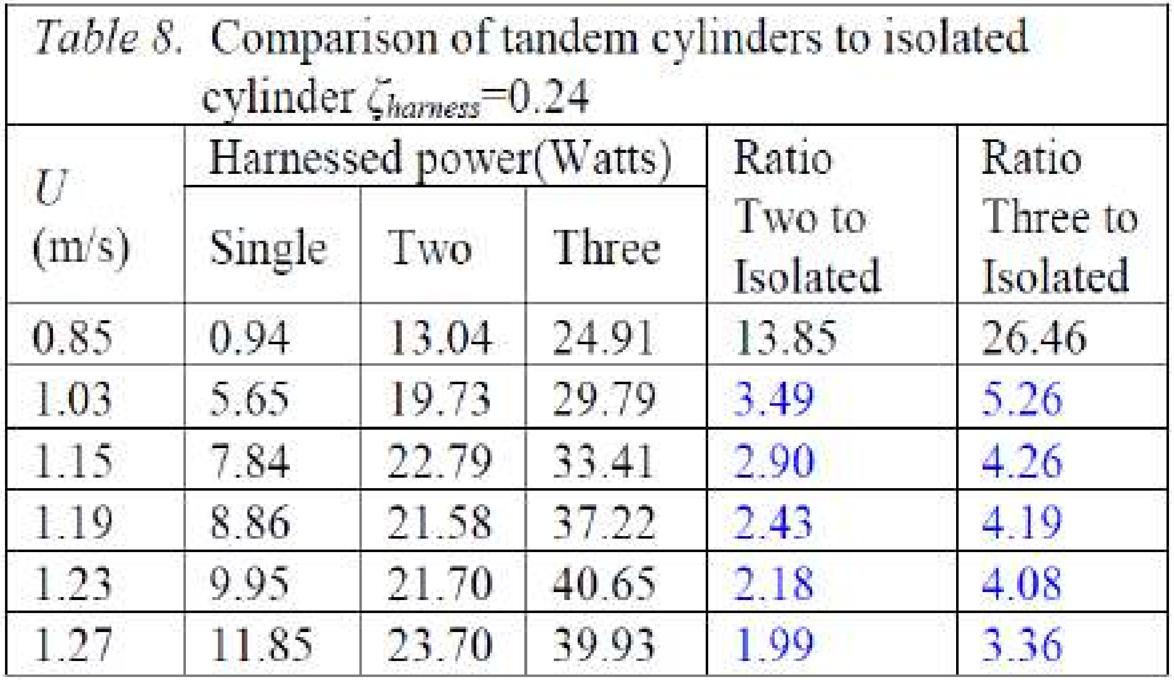


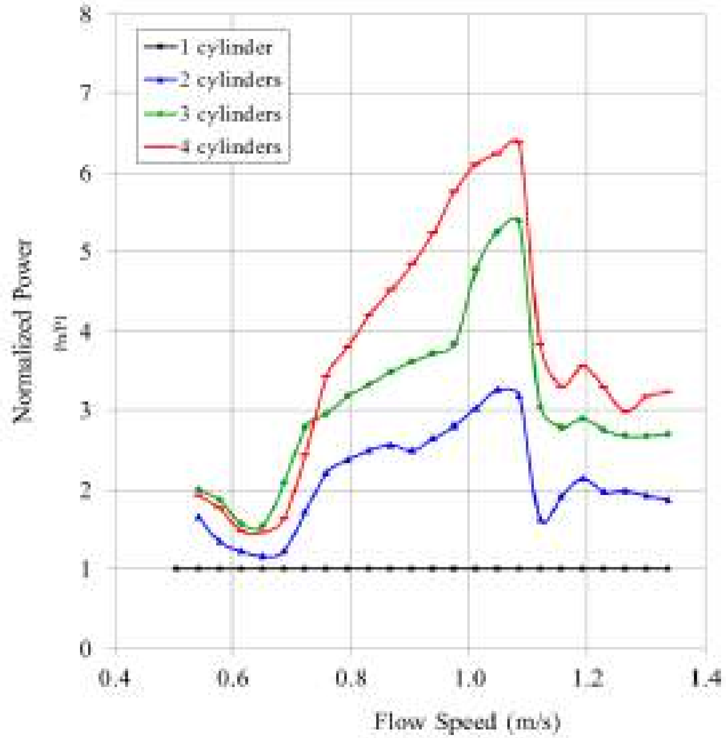
*Table 8.* Comparison of tandem cylinders to isolated cylinder $\zeta_{harness}$=0.24

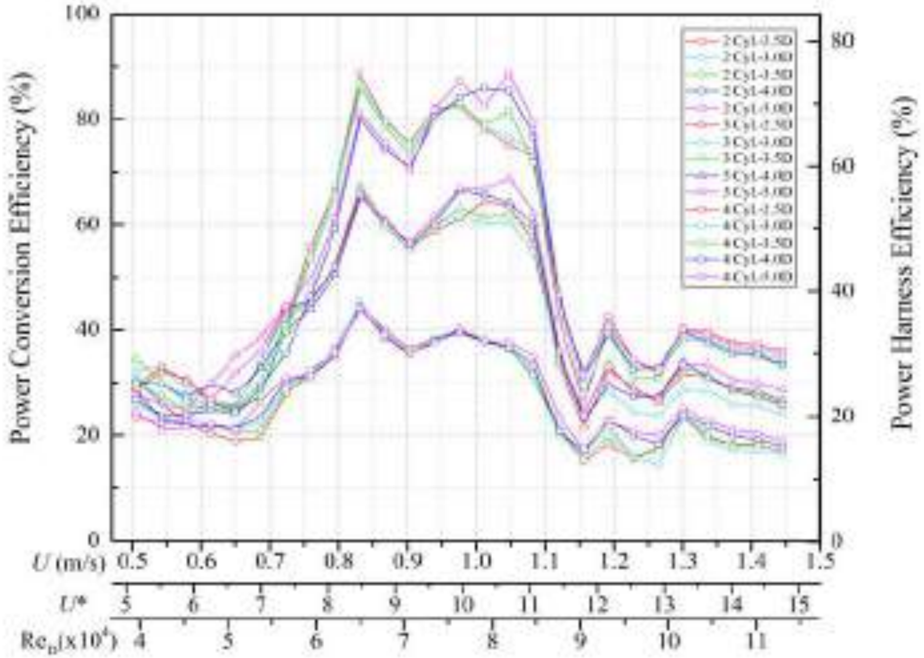
| *U* (m/s) | Harnessed power(Watts) | | | Ratio Two to Isolated | Ratio Three to Isolated |
|---|---|---|---|---|---|
| | Single | Two | Three | | |
| 0.85 | 0.94 | 13.04 | 24.91 | 13.85 | 26.46 |
| 1.03 | 5.65 | 19.73 | 29.79 | 3.49 | 5.26 |
| 1.15 | 7.84 | 22.79 | 33.41 | 2.90 | 4.26 |
| 1.19 | 8.86 | 21.58 | 37.22 | 2.43 | 4.19 |
| 1.23 | 9.95 | 21.70 | 40.65 | 2.18 | 4.08 |
| 1.27 | 11.85 | 23.70 | 39.93 | 1.99 | 3.36 |

# 5. Four-cylinder VIVACE

## Power amplification factor and efficiency [13] (VIV range – no PTC)

- Even w/o adaptive damping, multiple cylinder synergy can have a major beneficial effect
- Occupied space shrinks by a factor of 12-20
- Power-to-volume ratio increases by a factor of 30
- Efficiency can reach up to **88% of Betz limit**





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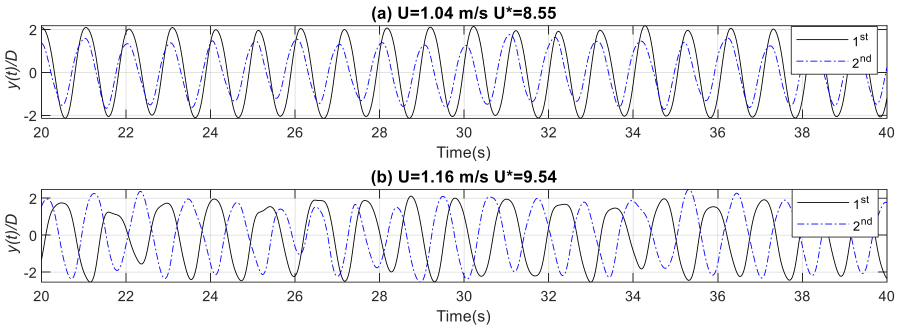
[13] Kim, E. S. and Bernitsas, M. M., “Performance prediction of horizontal hydrokinetic energy converter using synergy of multiple cylinders in flow induced motion”, Applied Energy 170 (2016) 92–100

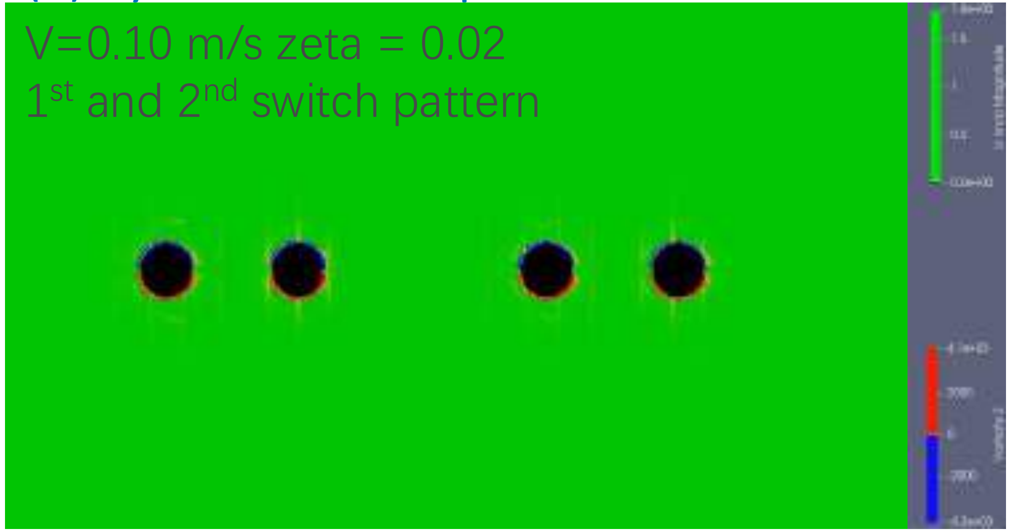
# II. UNDERYLING PHYSICS (9/15): 6. Other Observations

(a) 2nd cylinder may oscillate more than the 1st

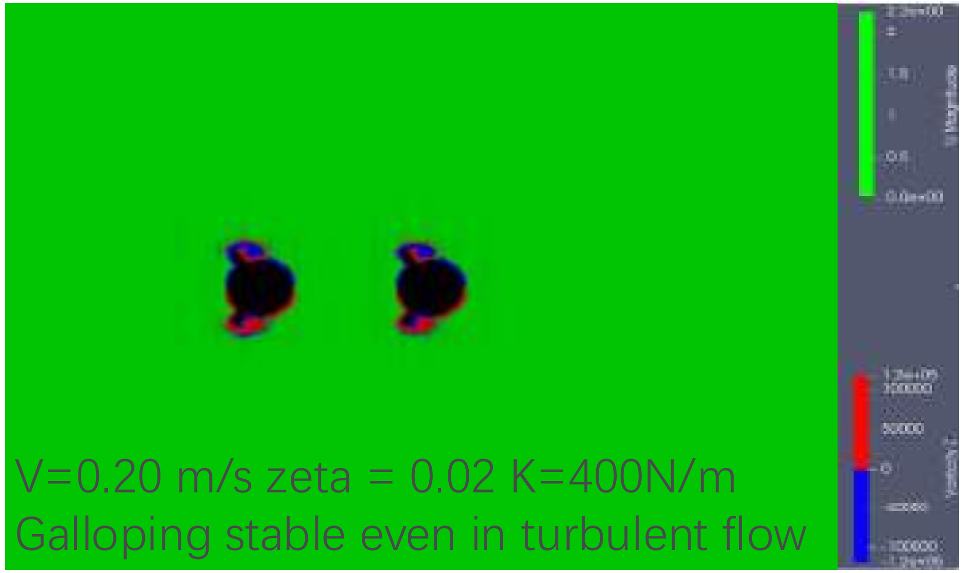


$K$=600N/m 1st cylinder $\zeta_{harness} = 0.24$ ,2nd cylinder $\beta = 25.0$

(b) Cylinders switch pattern



(c) Galloping stable even in turbulent flow



Synergy between cylinders for high-response is possible

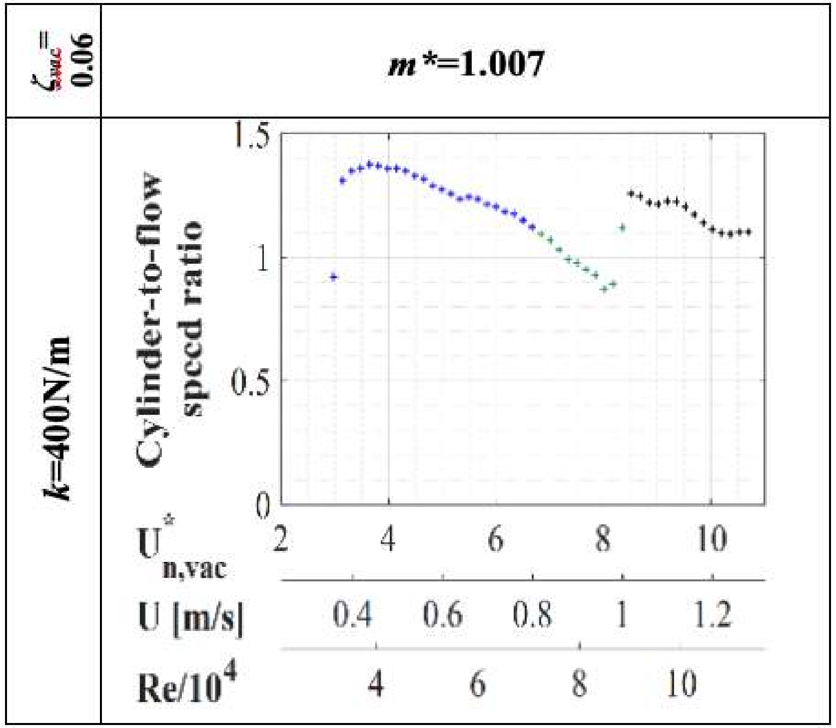
**Motion control** would not work due to numerous phenomena, bifurcations, and bi-stabilities

**Challenge:** How to implement results in an MHK Converter

# II. UNDERYLING PHYSICS (10/15): 6. Other Observations

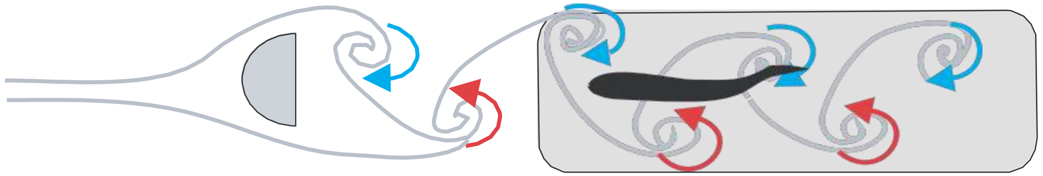
- **Moving body:** Cylinder is blunt; no blades
- **Tip speed:** All parts move at same speed; no rotor
- **Relative speed:** Even at $\zeta_{vac}=0.06$, $U_{cyl}<1.4U_{flow}$
- **Absolute speed:** At $U_{flow}=3\text{m/s}$, $U_{cyl}=4.2\text{m/s}$

(wind turbines 85m/s; HKT 40m/s)



Cylinder-to-flow speed ratio vs. *U,U* Re*

- **DOE study** (10y)**:** Harvard-MIT-ORNL conclusions [12]:
  - Fish relax - Spawn more - Thrive in cylinder wake
  - Get out of the wake only to catch food



- **VIVACE field-tests 2016:**
  - 3-month HK energy conversion
  - Invitations from communities to deploy

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[12] J.C. Liao, D.N. Beal, G.V. Lauder, M.S. Triantafyllou: Fish exploiting vortices decrease muscle activity, Science 302, 1566–1569 (2003)

# II. UNDERYLING PHYSICS (11/15): 7. Fish-school to cylinder-school

**Principles** applied to a school of cylinders on springs:

(P1) **Alternating lift** by two instabilities: VIO and galloping

(P2) **Enhancing instabilities** by turbulence stimulation

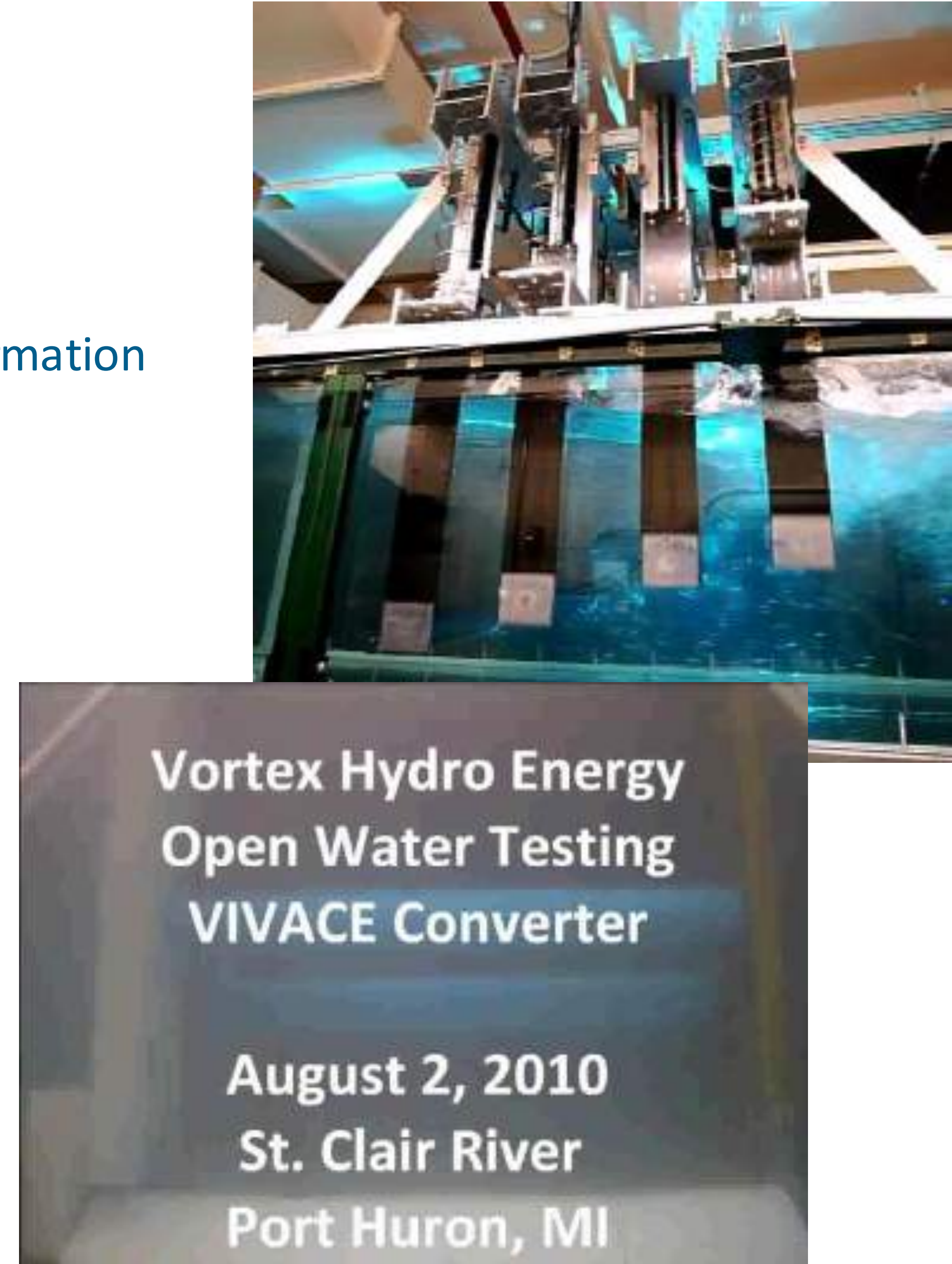
(P3) **Synergistic instabilities** and **wake gain** by cylinders in school-formation

(P4) **Adaptive damping**, passive or controlled [31,32]

**Objective:** *Mimic fish-school dynamics*
*w/o the complexity of fish-school kinematics*

**Methodology:**

*Match flow dynamics of cylinder-schools for MHK energy extraction to flow dynamics of fish-schools for minimal propulsion energy*



Vortex Hydro Energy
Open Water Testing
VIVACE Converter

August 2, 2010
St. Clair River
Port Huron, MI

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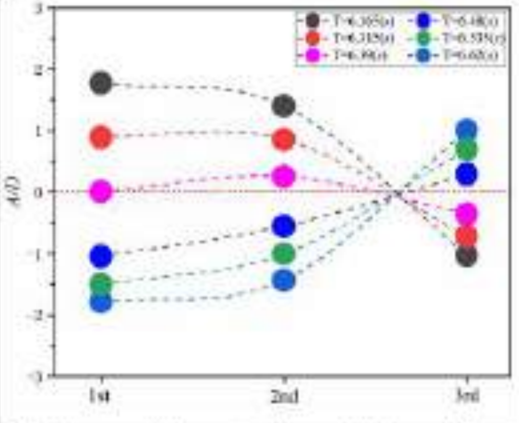
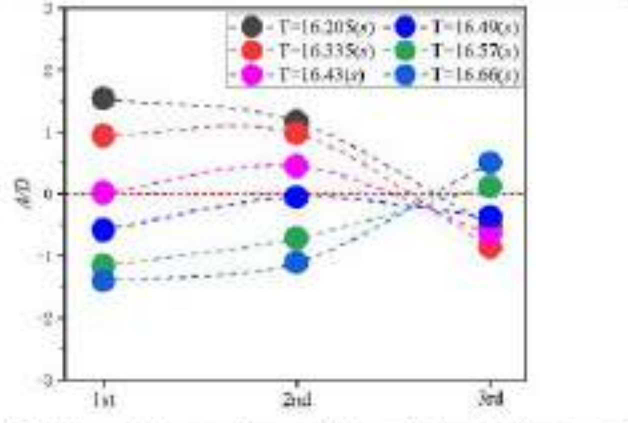
[10] Sun, H., & Bernitsas, M. M. (2019). Bio-Inspired adaptive damping in hydrokinetic energy harnessing using flow-induced oscillations. Energy, 176, 940-960.
[11] Hai Sun, M.M. Bernitsas, M. Turkol, "Adaptive Harnessing Damping in Hydrokinetic Energy Conversion by two Rough Tandem-Cylinders using Flow-Induced Vibrations", Renewable Energy, V149, April 2020, pp. 828-860.

# II. UNDERYLING PHYSICS (12/15): 8. High-response patterns

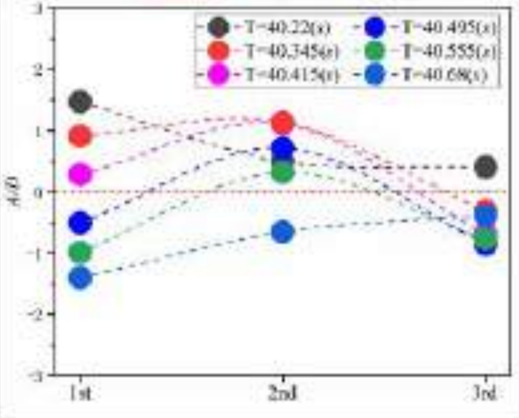
## We observed that high-response oscillatory patterns resemble fish-undulation



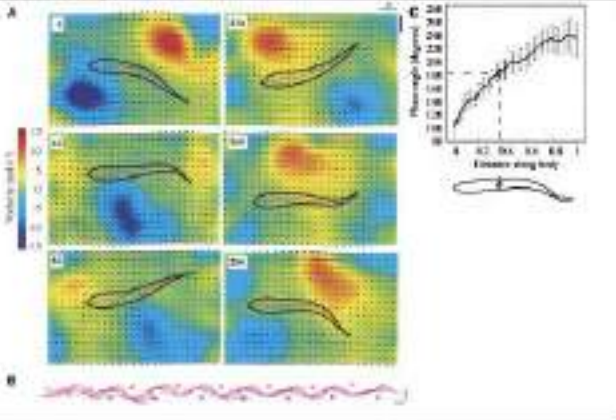
Positions of three tandem cylinders during half cycle of the first cylinder; $L/D$= 2.01, $K$=600N/m, $\zeta_{harness}$ = 0.24, $Re$ =114,000



Positions of three tandem cylinders during half cycle of the first cylinder; $L/D$=2.57, $K$=600N/m, $\zeta_{harness}$ = 0.24, $Re$ = 114,000.



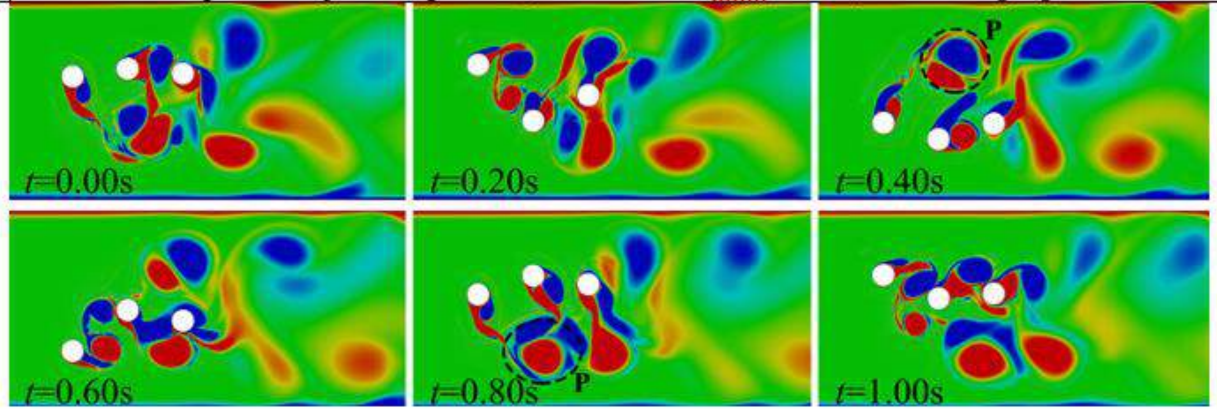
Positions of three tandem cylinders during half cycle of the first cylinder; $L/D$= 4.01, $K$= 600N/m, $\zeta_{harness}$ =0.24, $Re$= 114,000.



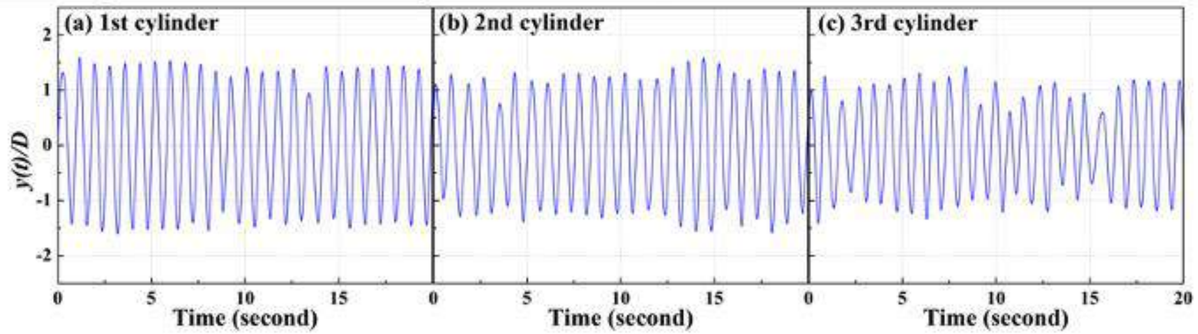
Interaction of trout with cylinder vortices

J.C. Liao, D.N. Beal, G.V. Lauder, M.S. Triantafyllou, "Fish Exploiting Vortices Decrease Muscle Activity", Science 302(5650) (2003) 1566-1569.

Undulated shape of 3-cylinder pattern; $K$=750N/m, $\zeta_{total}$ =0.02, $m^*$=1.68 [12]



Vortex pattern for three PTC-cylinders at $Re$=62,049

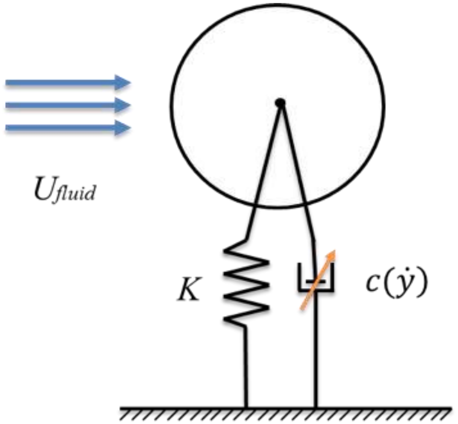


Displacement history of three PTC-cylinders at $Re$=62,049

# II. RESEARCH ADVANCES (13/15): 5. Adaptive damping

## Velocity-dependent damping coefficient …..

….. a bio-inspired approach to MHK energy harvesting

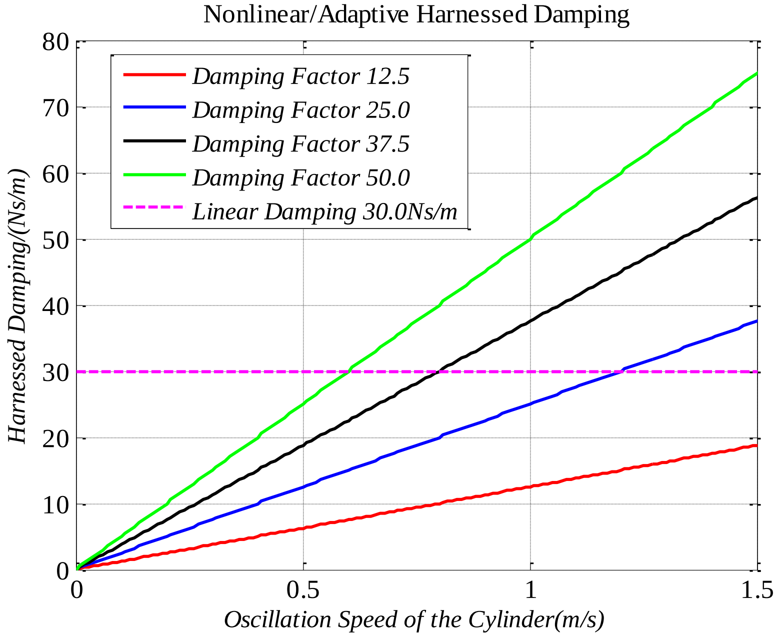


**Fish adjust** their flexing/undulation speed to inflow speed
for min. energy expenditure

**VIVACE adjusts** its damping coefficient based on its oscillation
speed for max. energy harnessing

Slow oscillation … low damping … little harnessing
(effective at onset and transition from VIV to galloping)

Fast oscillation … high damping … a lot of harnessing
(effective at onset and transition from VIV to galloping)



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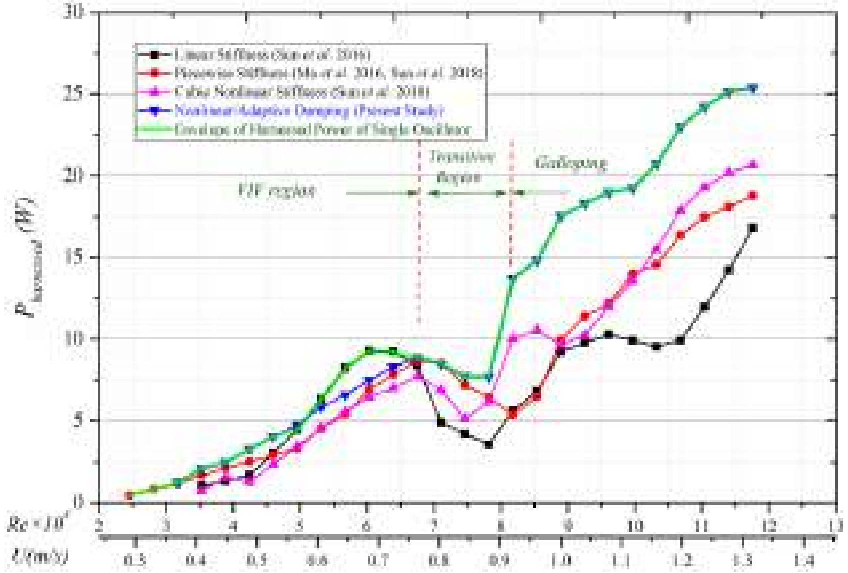
[10] Sun, H., & Bernitsas, M. M. (2019). Bio-Inspired adaptive damping in hydrokinetic energy harnessing using flow-induced oscillations. Energy, 176, 940-960.

[11] Sun,H., M M. Bernitsas, M Turkol, "Adaptive Harnessing Damping in Hydrokinetic Energy Conversion by two Rough Tandem-Cylinders using Flow-Induced Vibrations", Renewable Energy, V149, April 2020, pp. 828-860.

# 5. Adaptive damping

## Adaptive damping increased power:

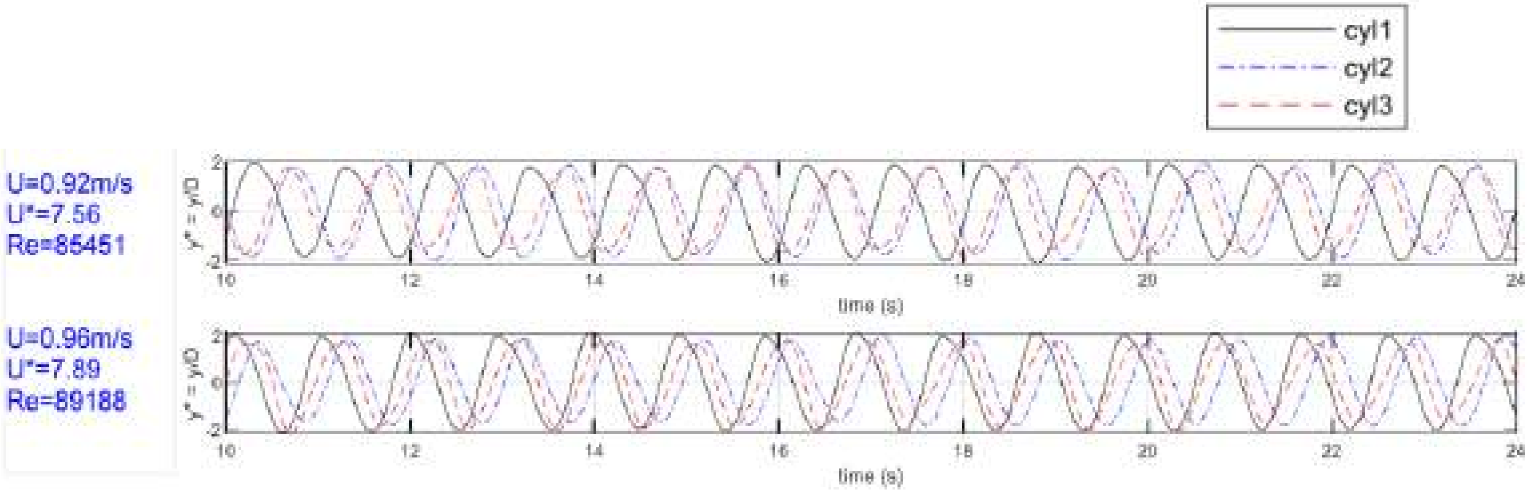
- Early VIV onset
- Expanded synchronization VIV range
- Early galloping onset
- In transition, 128% increase in $P_{harness}$
- In galloping, 51% - 95% increase in $P_{harness}$



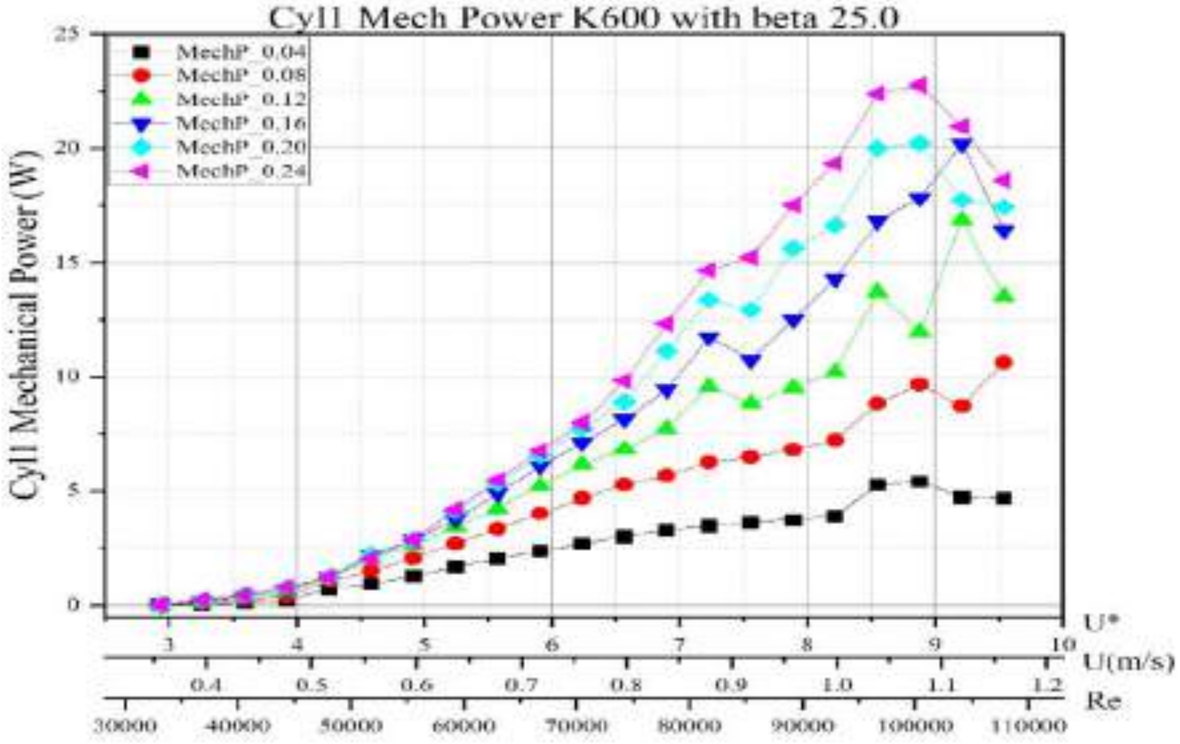
**Power envelope of a single-cylinder converter with:**
(a) linear stiffness, (b) 3 nonlinear stiffness models, and (c) adaptive harnessing damping.

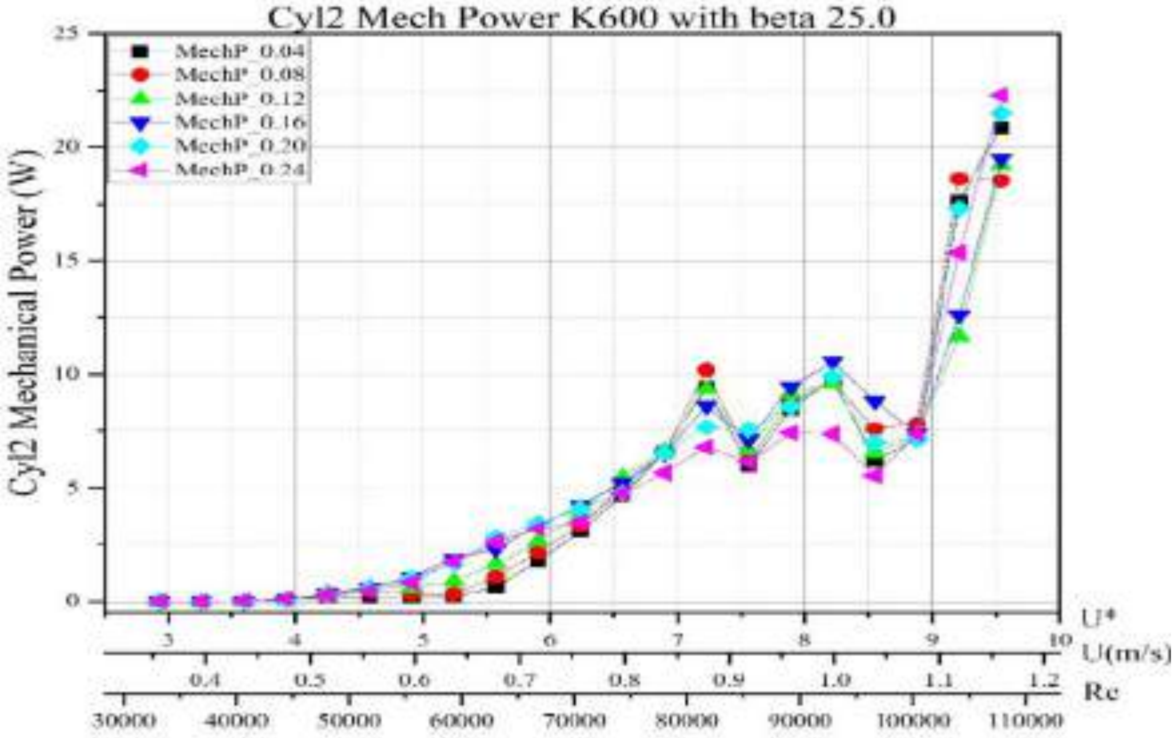
## Most Important:

- Adaptive damping makes cylinders precipitate into interaction modes leading to oscillatory patterns identical to fish undulation
- It is passive (c=$\beta\dot{y}$)
- Does not interfere with natural FIOs
- Works for all speeds and parameters



# II. RESEARCH ADVANCES (15/15): 5. Adaptive damping


Cyl1 Mech Power K600 with beta 25.0


Cyl2 Mech Power K600 with beta 25.0

**Mechanical power of cylinders:** 1st cylinder with parametric linear damping $\zeta_{harness}$.

2nd cylinder with adaptive damping $\beta = 25.0$

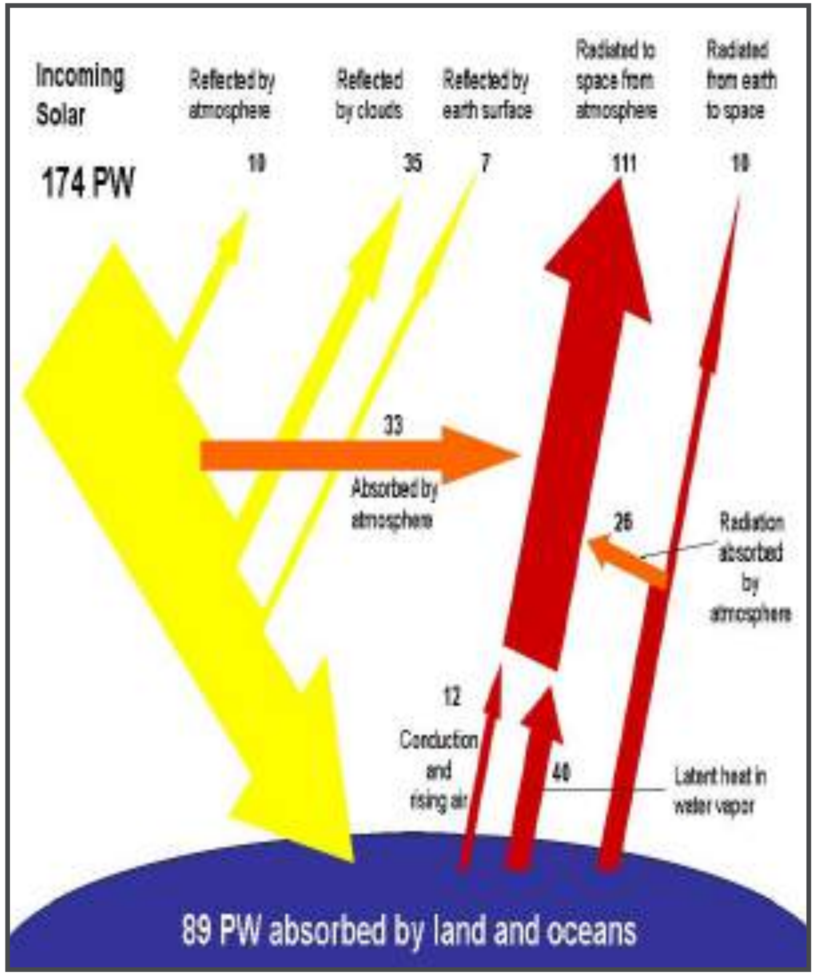
Power extracted by 2nd cylinder is nearly independent of the power extracted by the first

# III. Marine Hydrokinetic Energy

- How much
- Where is it
- Horizontal MHK: In rivers, ocean currents, and tides
- Vertical MHK energy: In waves

# III. MHK (1/3): Energy Source

## • Energy from the Sun [14]



## • Energy absorption on Earth

**Solar energy** to Earth:
3,770 ZJ/y (119.5 PW)

**Oceans** absorb:
365 ZJ/y (11.6PW)

**Winds** can supply:
6 ZJ/y (0.19PW)

**Biomass** captures:
1.8 ZJ/y (0.057 PW)

**World consumption:**
0.57 ZJ in 2018

## • How much is in the Oceans?

| **Energy** [15,16] | **TWh** | **ExaJoules** |
|---|---|---|
| Tidal | 22,000 | 79 |
| Wave | 18,000 | 65 |
| Thermal | 2,000,000 | 7,200 |
| Salt gradient | 23,000 | 83 |
| **Total** | **2,063,000** | **7,400** |

World:
electricity (2017) 21,372 TWh
energy consumption (2018) 157,064 TWh

2 TW harnessable from the world's ocean currents (total available 5TW)

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[14] Renewables 2007 Global Status Report; Worldwatch Institute
[1ZJ=$10^{21}$Joules; 1kWh=0.278*$10^{15}$J

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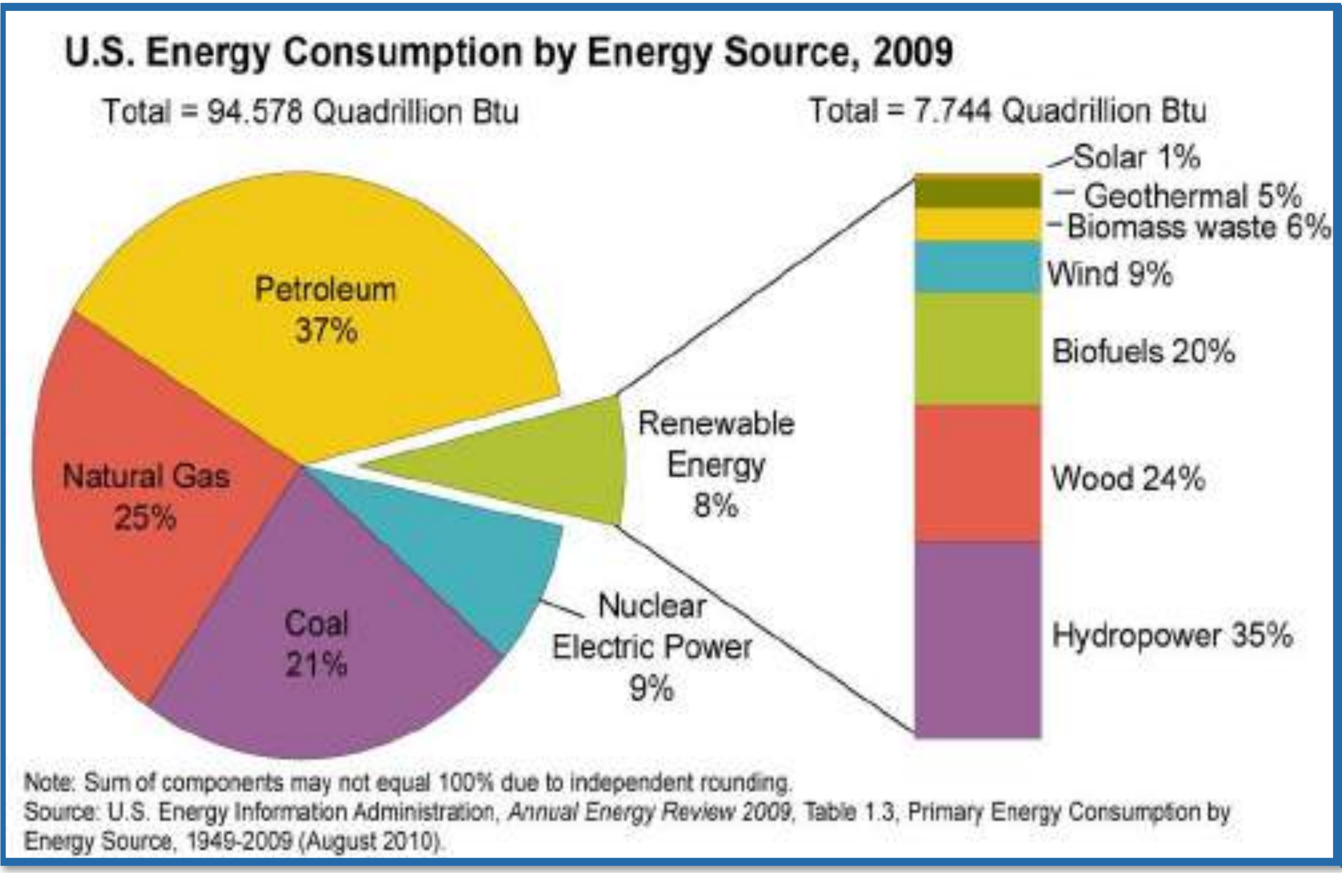
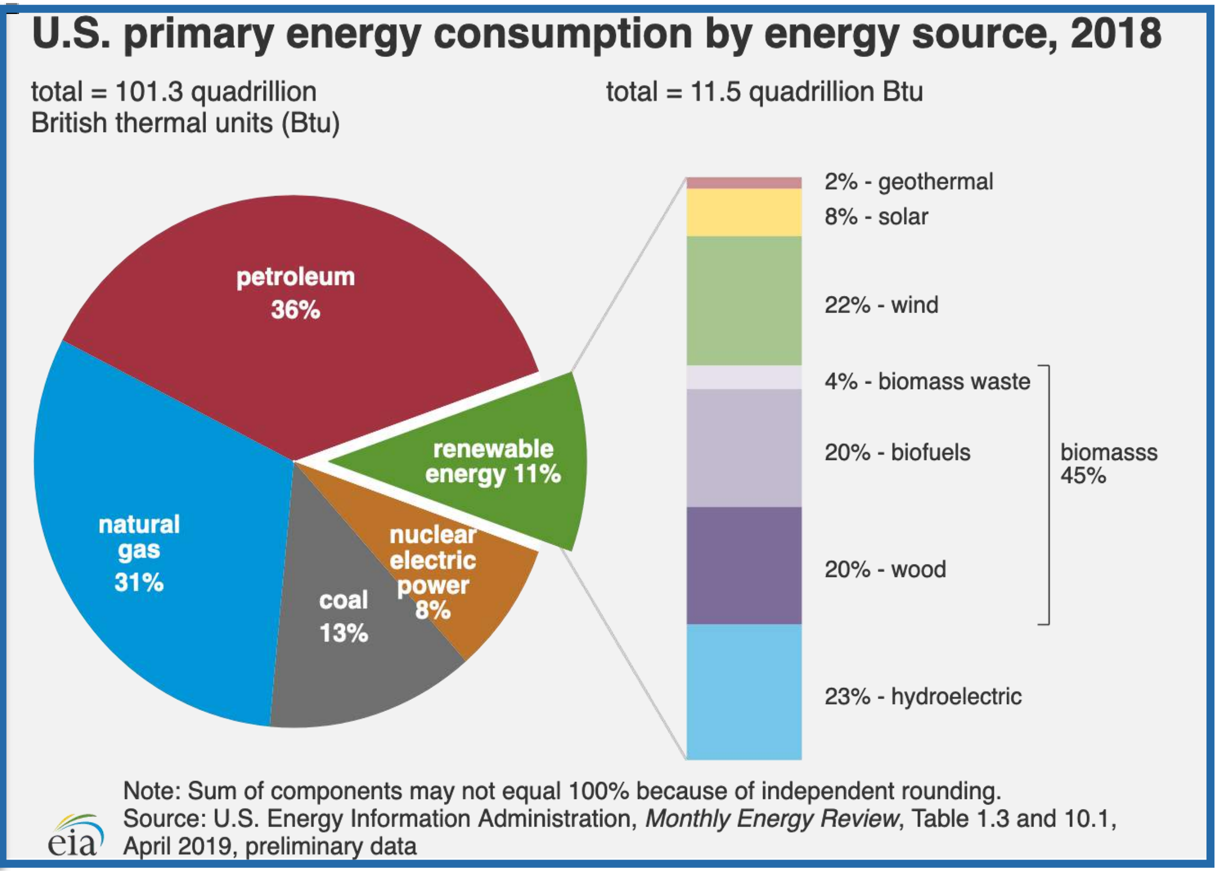
[15] https://www.iea.org/reports/electricity-information-overview
[16] EPRI data: present technology; no loss due to mechanical efficiency; no accessibility restrictions; Hydrokinetic & Wave Energy Technologies Workshop, Oct 26-28, 2005, WDC

# III. MHK (2/3): Energy Consumption



U.S. Energy Consumption by Energy Source, 2009

Note: Sum of components may not equal 100% due to independent rounding.
Source: U.S. Energy Information Administration, *Annual Energy Review 2009*, Table 1.3, Primary Energy Consumption by Energy Source, 1949-2009 (August 2010).



U.S. primary energy consumption by energy source, 2018

Note: Sum of components may not equal 100% because of independent rounding.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2019, preliminary data

**2009: Hydrocarbons account for 83%**

**2018: Hydrocarbons account for 80%**

# III. MHK ENERGY (3/3): Horizontal MHK near shores - USA

$$Power_{flow} = \frac{1}{2}\rho_{water} U^3_{flow} Area$$

**In the USA:** MHK energy is considerable[6]

- Theoretical amount : 2051 TWh/yr (7 Quad/yr)
- Practically extractable: 615 TWh/yr (2.1 Quad/yr)

| (In Quads/y)[6] | **Theoretical** | **Practical** |
|---|---|---|
| **Tidal Streams** | **1.5** | **1.1** |
| **Riverine Currents** | **4.7** | **0.4** |
| **Ocean Currents** | **0.7** | **0.6** |
| **Total** | **7.0** | **2.1** |

**Increase** the practical amount

- Share water for different usage
- Decrease minimum current velocity for Converters

**Usage in the Blue Economy:** *"the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems."* (World Bank)

Co-located with Horizontal MHK energy

- Deep-sea oil/gas operations • Ocean floor and seawater mining
- Autonomous underwater vehicle support • Climatological observation
- Aquaculture • Desalination
- Disaster recovery • Powering isolated communities

**Horizontal MHK remains largely untapped; many challenges**

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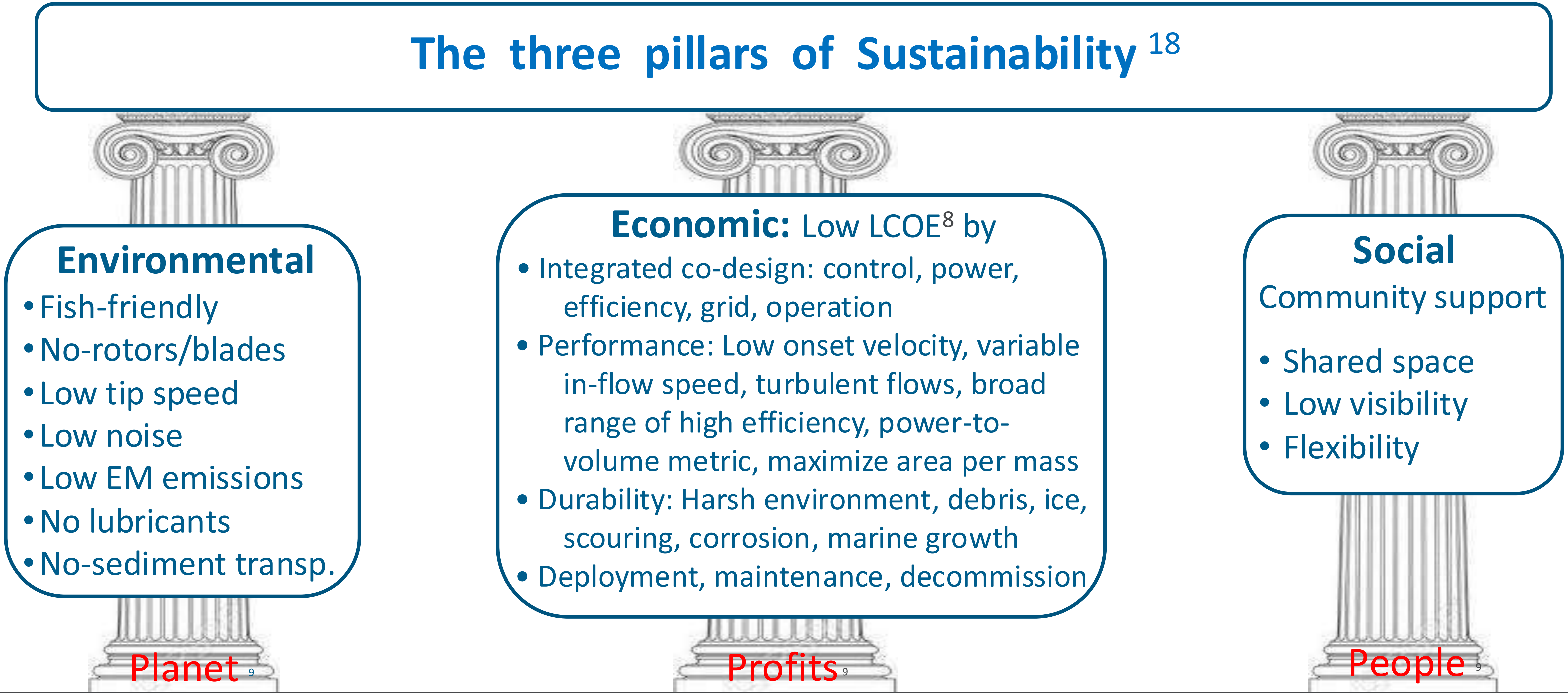
[17] Quadrennial Energy Review 2015: Marine and Hydrokinetic Energy, U.S. Department of Energy, Washington, DC

# IV. Challenges

- Sustainability: environmental compatibility + clean energy, slow flows
- Fish-friendly technology: rotors, blades, high tip-speed
- LCOE target: reduction by 60%
- Slow flows: 0.5-1.5m/s

# IV. CHALLENGES (1/3): Sustainability

- Avoid depletion of natural resources to maintain an ecological balance [18]
- Meet present needs without compromising the needs of future generations



**The three pillars of Sustainability [18]**

**Environmental**

- Fish-friendly
- No-rotors/blades
- Low tip speed
- Low noise
- Low EM emissions
- No lubricants
- No-sediment transp.

**Economic:** Low LCOE[8] by

- Integrated co-design: control, power, efficiency, grid, operation
- Performance: Low onset velocity, variable in-flow speed, turbulent flows, broad range of high efficiency, power-to-volume metric, maximize area per mass
- Durability: Harsh environment, debris, ice, scouring, corrosion, marine growth
- Deployment, maintenance, decommission

**Social**

Community support

- Shared space
- Low visibility
- Flexibility

Planet[9] Profits[9] People[9]

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[18] investopedia.com/terms/s/sustainability.asp [8] DOE, ARPA-E, April 9, 2020, DE-FOA-0002334 [9] pinterest.com/pin/864198615981243884/

# IV. CHALLENGES (2/3): LCOE is the key to success

**Objective**[19] Low LCOE = (CapEx+OpEx)/AEP

## State of the art of HK Turbine technology [8]

| Presently | Objective | |
|---|---|---|
| • $0.1671/kWh | $0.065/kWh | for riverine systems at utility scale |
| • $0.1037/kWh | $0.040/kWh | for tidal-stream systems at utility scale |
| • $0.2115/kWh | $0.085/kWh | for riverine systems in remote areas |
| • $0.2477/kWh | $0.105/kWh | for tidal-stream systems in remote areas |

**Reduction of about 60% in LCOE is required**

**A tough problem with a target of 2030**

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[19] Garcia-Sanz, M., (2020). A Metric Space with LCOE Isolines for Research Guidance in wind and hydrokinetic energy systems. Wind Energy, Vol.23, No.2, pp.291-311, Wiley

# IV. CHALLENGES (3/3): What can VIVACE do?

- **CEC** (Current Energy Converter); also called **HKT** (Hydrokinetic Turbine)
- Harness horizontal **MHK** (Marine Hydro-Kinetic) energy
- Simple to build: array of 1-4 oscillators of cylinders with turbulence stimulation and PTO
- Controls natural instabilities to match fish dynamics w/o the complexity of fish-kinematics
- Based on 4 fish biomimetic principles
- Fish-friendly: No blades, no rotor; blunt body;
  $U_{cyl}$<1.2$U_{flow}$ (fast flows ); $U_{cyl}$<1.4$U_{flow}$ (slow flows)

- Highly scalable (40 < $Re$ < ∞)
- Provide access to a vast & untapped energy source:
  Most currents < 3knt (rivers <2 knt)

- Onset at flow as slow as 0.19m/s (no upper limit)
- High power-to-volume ratio: VIVACE=602W/m$^3$ (@1.3m/s)
  Wind farms=0.01W/m$^3$ (@12m/s); Diesel=25kW/m$^3$

- Compact, working as a 3-D energy converter
- Reaches efficiency up to $\eta$=88% of Betz limit

# V. Design Considerations

- Local optima: Efficiency vs. power
- 1st generation VIVACE
- 2nd generation – portable
- Applications: The Blue Economy

# V. DESIGN (1/6): Optimal Power or Efficiency

H. Sun et al. / Renewable Energy 149 (2020) 828–860

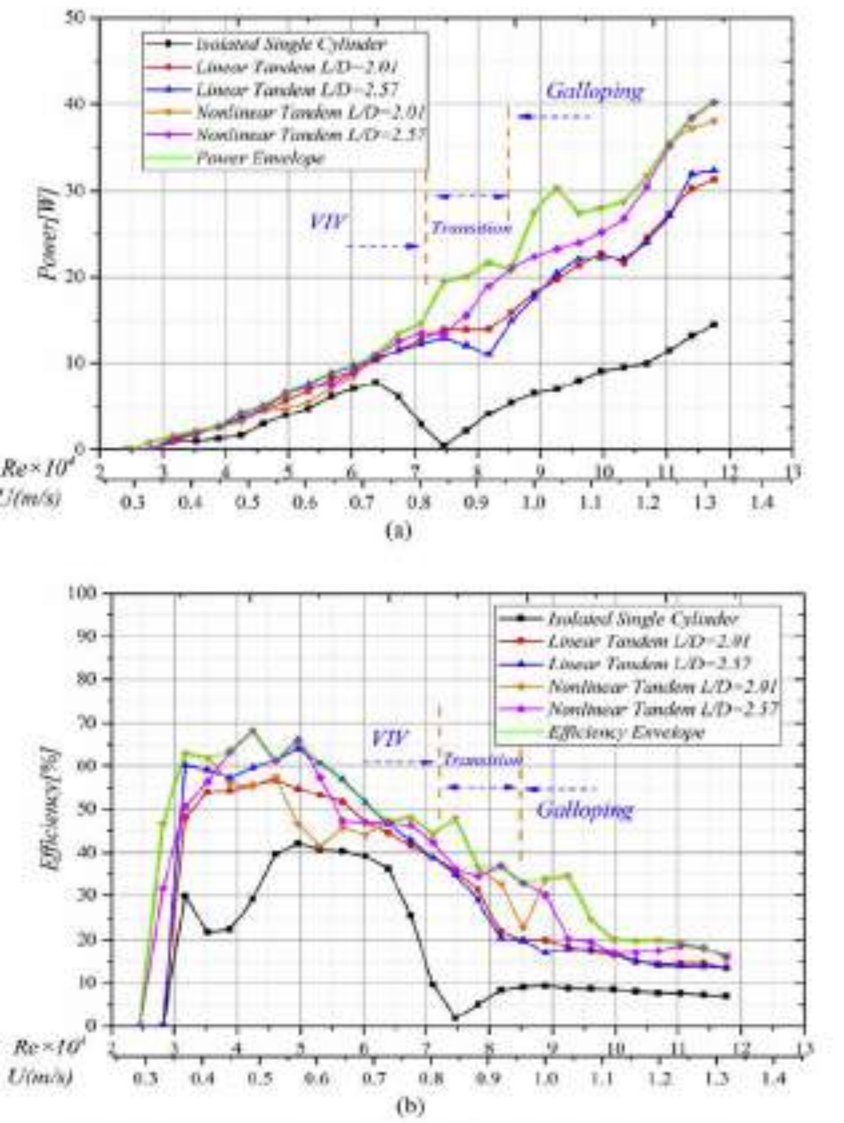


Fig. 24. Optimal synergistic FIO for power and efficiency for linear and nonlinear harnessing damping.

**Optimal synergistic FIO for power & efficiency for linear & adaptive harnessing damping[32]**

## Power & Efficiency[32]

- Increases ability to harness hydrokinetic energy
- Mitigates shielding effect on downstream cylinder doubling its power
-

| At higher $U_{flow}$ | $P_{harness}$ | $\eta_{harness}$ |
|---|---|---|
| VIV to galloping transition | up 46% | up 34% |
| initial galloping | up 33% | up 94% |
| Fully developed galloping | up 35% | up 33% |

## Expanded RAO range[32]

- $P_{harness}$ initiated with VIV at $U_{flow}$=0.31 m/s (*Re*=28,100)
- Stable power without gaps/drops in transition regardless *C* or *K*
- Width of FIO regions (VIV, transition, galloping) did not change with *C* or *K*
- Compensates for local/temporal $U_{flow}$ variation
- Prevents suppression of amplitude and, thus, power modulation

# V. DESIGN (2/6): 1ST GENERATION VIVACE

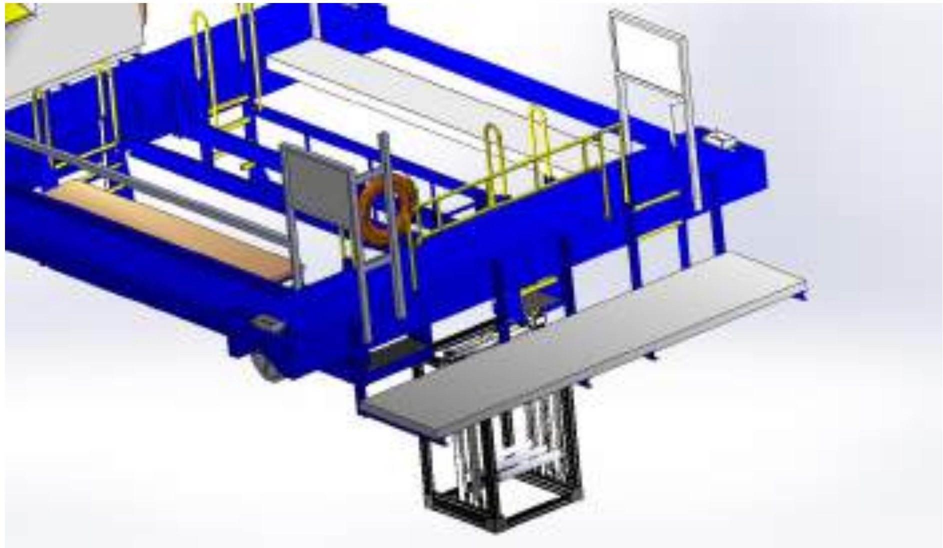
## St. Clair River, Port Huron, MI. June-September 2016

# V. DESIGN (3/6): $2^{ND}$ GENERATION PORTABLE

**A unique feature of the MRELab and VIVACE is the *Vck*** (2009, 2014)

- Emulates spring stiffness ***k*** and damping ***c*** of any mathematical model linear or nonlinear and their parameters
- Quick change of oscillator parameters for testing or adaptation to excitation
- Use of the same physical equipment to harness energy from currents or waves
- Redesigned to merge motor, generator, and controller for high $\eta_{Vck}$

Channel testing at MRELab



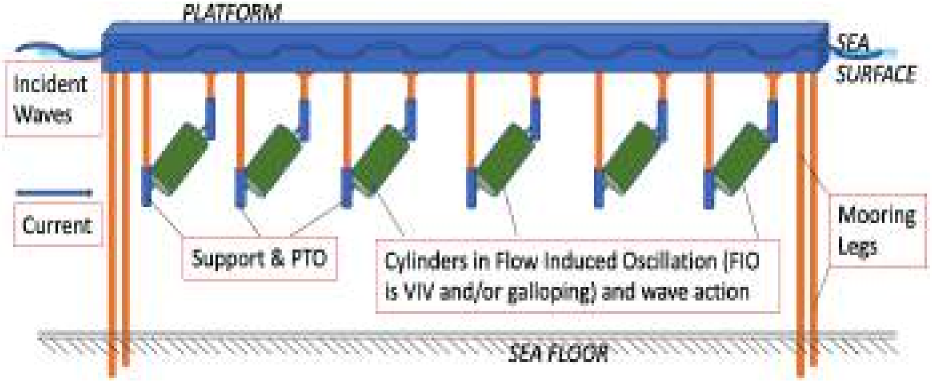
TEAMER Project to test at MHL
Test at Pacific Northwest NL of DOE

Dry testing at Vortex

# V. ADVANTAGES (4/6): VIVACE-W

## **VIVACE-W:** The only device that can extract energy from both waves and currents

Basic VIVACE configuration
Horizontal cylinders supported by a buoy
Cylinders are designed so they are at resonance with waves & currents



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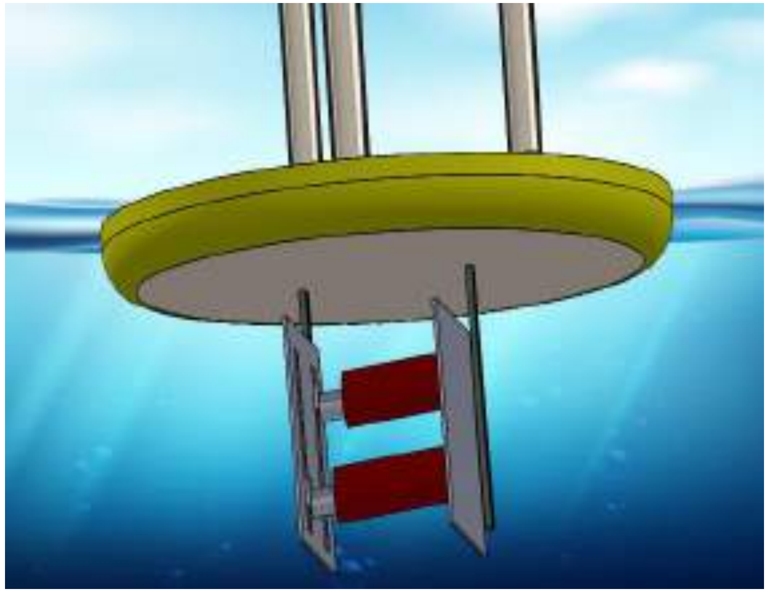


**VIVACE-W 3:** 3 horizontal cylinders, D = 1.5m, L = 12m so that cylinders can be road-transported

**Power generated in currents**

| Velocity [m/s] | Power [kW] |
|---|---|
| 1 | 20 |
| 1.5 | 68 |
| 2 | 164 |

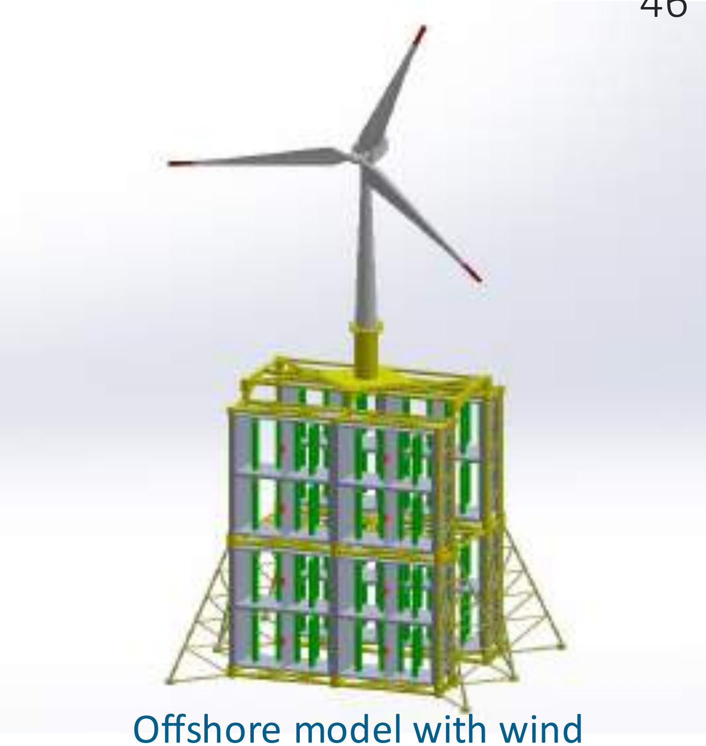
**Power generated in waves**

| Significant wave height [m] | Power [kW] |
|---|---|
| 1 | 17.2 |
| 2 | 69 |
| 3 | 155 |

# V. VISION (5/6): Target Markets

- **Remote coastal areas and island communities**
  - 2005 study at the University of Alaska Fairbanks:
  - Alaskan communities generated 374,207 MWh by diesel generators
  - Alaska has over 365,000 miles of rivers and 33,000 miles of coastline
  - VHP sees potential to deploy the VIVACE-W
- **Renewable power for buoys**
  - VIVACE-W can be mounted under a weather buoy to power it

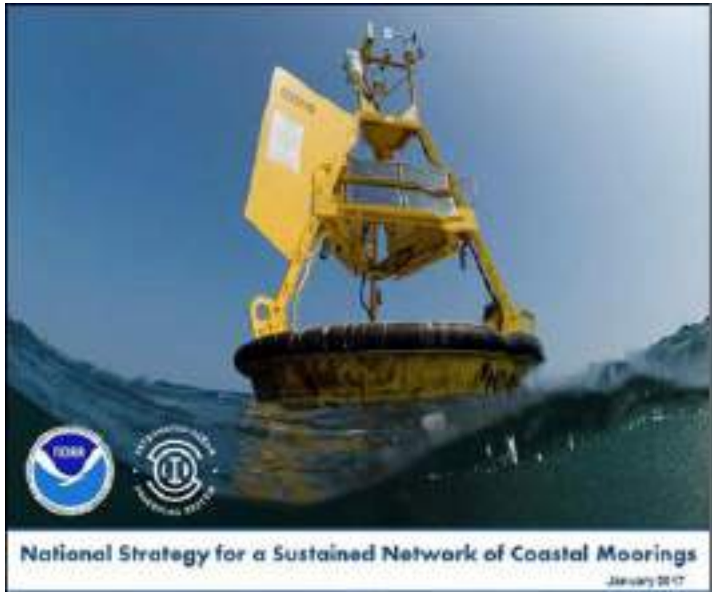
NOTE: Power/batteries account for 50 % of limitations to ocean observation



Offshore model with wind platform: 1,500kW

- **Autonomous underwater vehicles power needs**
- **Aquaculture farm power needs**
- **Department of Defense (DOD)**

**VIVACE can be scaled down** and support the DOD need for portable hydroelectric generators.



National Strategy for a Sustained Network of Coastal Moorings

# V. DESIGN (6/6): PATENTS

## For 2973: “Converter of Current/Tide/Wave Energy”

US Patent 7,493,759
US Patent: 8.047,232
Netherlands Patent: 1812709
France: Patent# 1812709
Germany: Patent# 602005039182.7
United Kingdom: Patent# 1812709

## For 3737: “Enhancement of Vortex Induced Forces and Motion”

US Patent: 8,047,232

## For 3757: “Reduction of Vortex Induced Forces and Motion”

US Patent: 8,684,040

## For 2018-319:“Contact-Less Magnetic Supports for Marine Hydrokinetic Energy Harvesting Using Flow Induced Oscillation”

US Patent: 11,143,158 B2

## For 2022-054: “Marine Hydrokinetic Energy Harvesting Using Flow Induced Oscillations and Waves”

US Patent: 18/128,293, May 1, 2024

## For 2022-268: “Marine Hydrokinetic Energy Harvester with Multiple VIVACE Oscillators in Synergy”

Patent Application # PCT/US2024/013668, US Patent and Trademark Office, 1/31/2024.

# THANK YOU for your attention

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DOE

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