Status of the VIVACE Converter: Current and wave energy harvester using fluid structure interaction and fish-bioinspired control

Tuesday, 13 September 2022

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Track 2, Session 2 11:45am-1:15pm

OUTLINE

I. 1ST GENERATION VIVACE CONVERTER (2016)

- Field tests in the St. Clair River

II. UNDERLYING PHYSICS

- Lift: alternating vs. steady
- Complexity: hydro vs. geometry, fish vs. cylinders
- Flow Induced Oscillations: VIV & galloping
- Cylinder-schools: synergistic FIO

III. 2ND GENERATION SUBSYSTEMS

- Hydrodynamics: Achievable?
- Turbulence Stimulation: Slow flows
- Control: Oscillator properties not motion
- Magnetic Restraint: Counter drag/friction
- Magnetic Gear: Dry/wet environments
- Power Electronics: Signal conditioning
- Frame: Durable, easy to assemble & attach

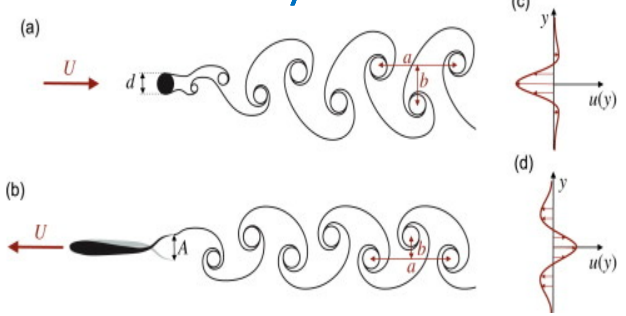
CLOSING REMARKS

- Versatility: Currents & Waves
- Portability: Modularity & Assembly

I. 1^{ST} GENERATION VIVACE: 2016 field tests

II. UNDERLYING PHYSICS (1/4): Alternating lift & instabilities

Fish.... steady flow flex body alternating lift

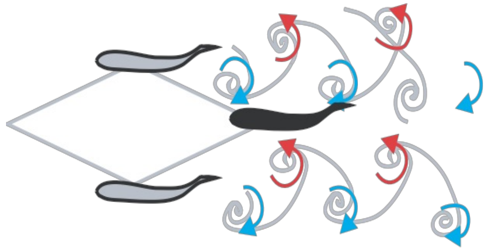


Thrust wake

vs.

drag wake

Black fish utilizes thrust-wake generated by the two gray fish



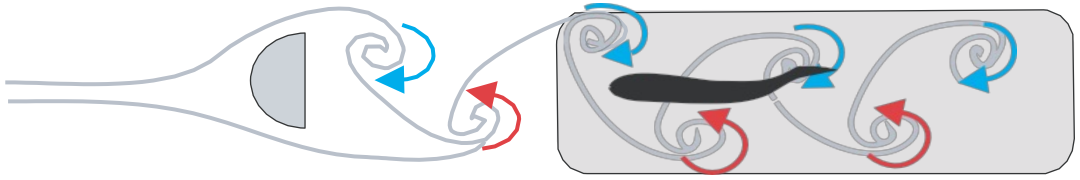
Gray-fish: drag-wake

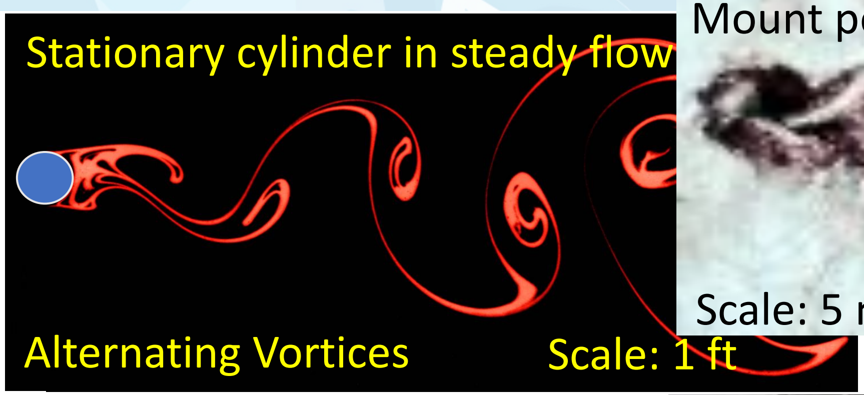
Black-fish: in a thrust-wake

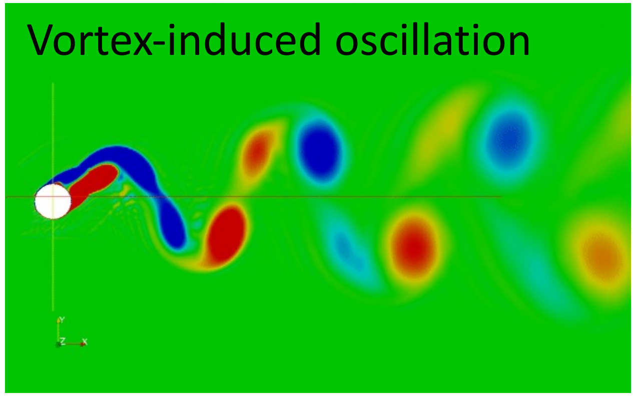
Gray-fish: drag-wake

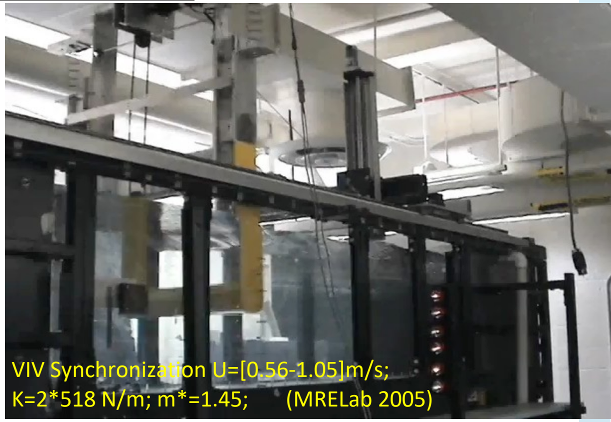
Fish relax, spawn more, thrive in cylinder wake

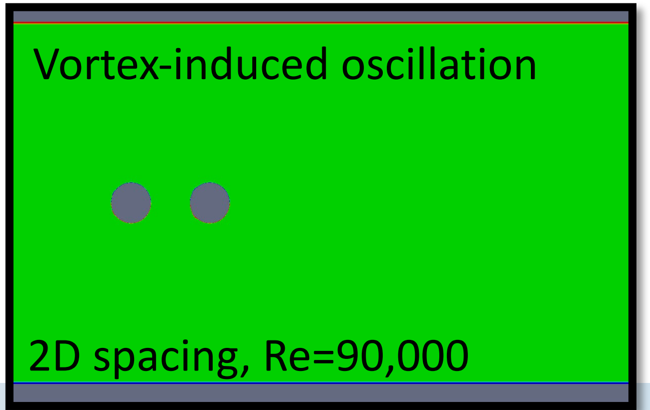
(DOE-Harvard-MIT, 10-year study)

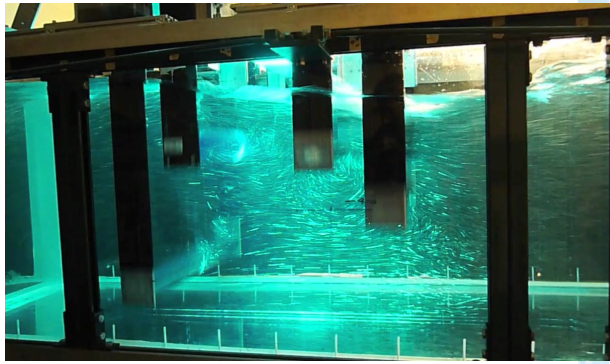












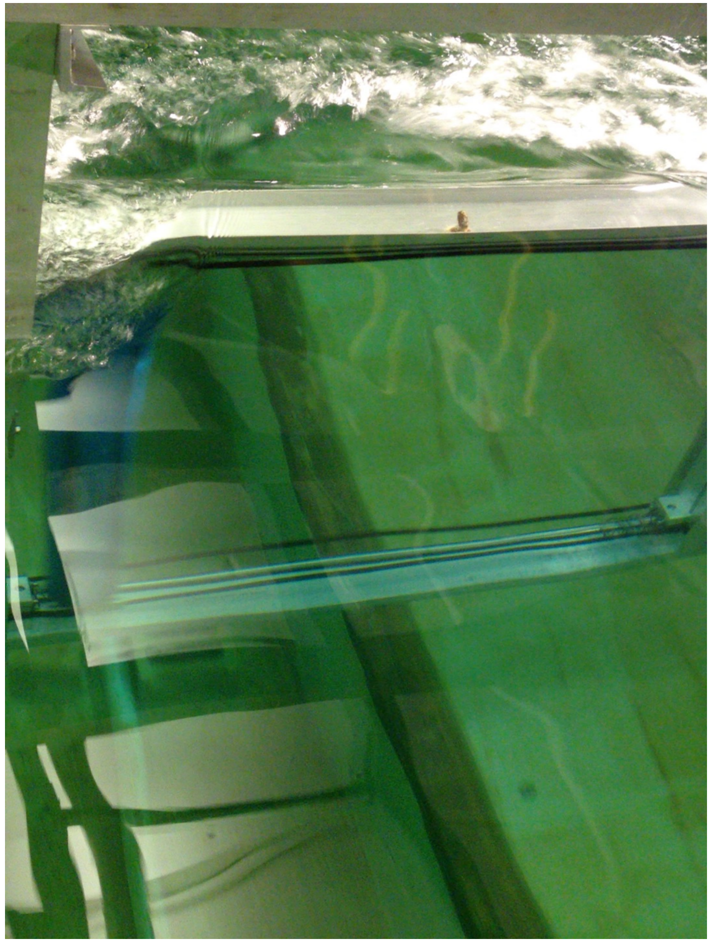
Weihs, D. ***Nature*** 241, 290-291

II. UNDERLYING PHYSICS (2/4): VIV & galloping

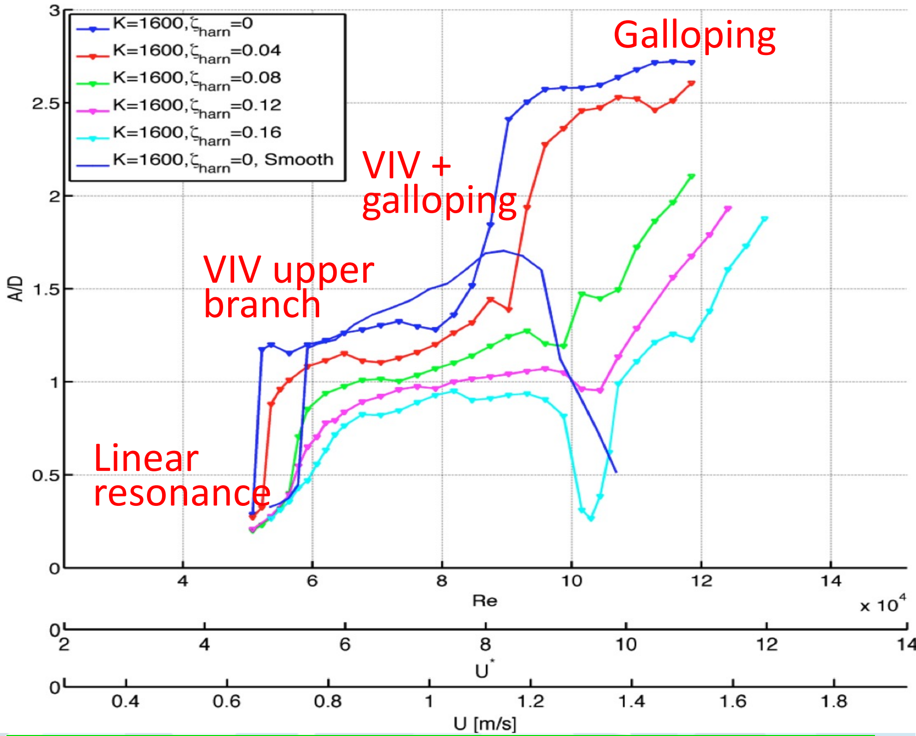
Non-circular cylinders may gallop perpendicular to flow

- VIV vs. galloping
  - Cause: in VIV, Vortex shedding
    in galloping, shear layer motion
  - *U*:* in galloping $U^*_g < U^*$[28]

    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 $f_{n,vac}$

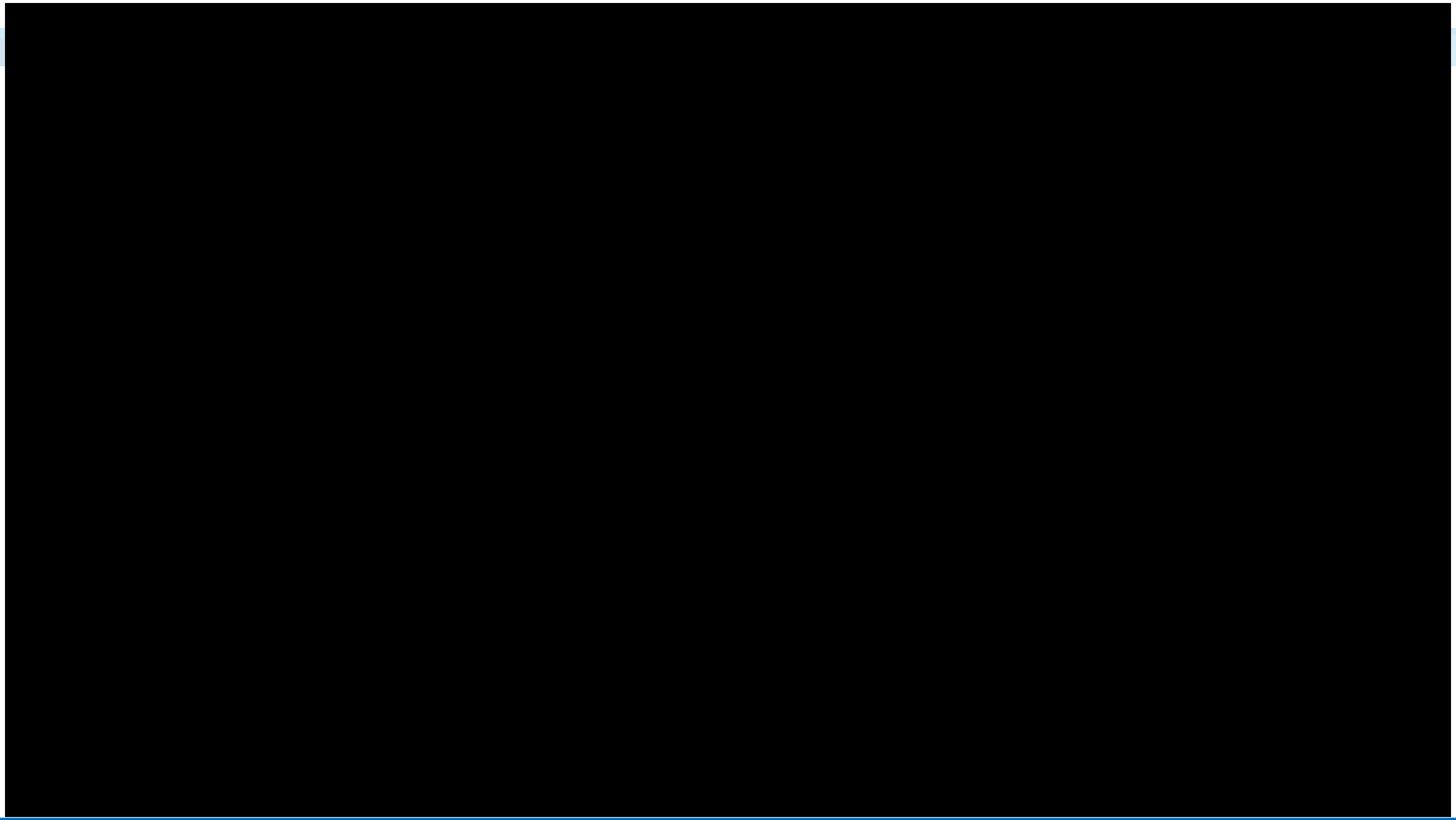


- Transition VIV to galloping
  - Cause: gap in FIO
    coexistence of mechanisms



II. UNDERLYING PHYSICS (3/4): Interference & Synergy

Cylinder-schools:



- Oscillating bodies
- Oscillating stagnation points
- Boundary layers
- Oscillating separation points
- Shear layers
- Rolling up shear layers
- Von Kármán vortices
- Alternating wake

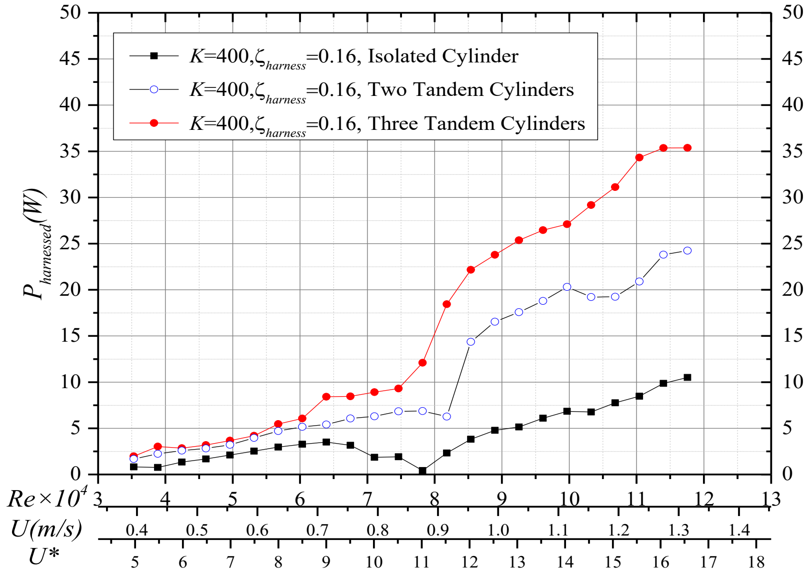
Fish-schools: Efficient dynamics but complex kinematics (body undulation)

Cylinder-schools: Complex dynamics but simple kinematics (oscillators)

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

II. UNDERLYING PHYSICS (4/4): Synergy

Spacing L/D=2.57: In galloping, 3 cylinders generate **3.6-5.8** times the power of a single cylinder



K=400N/m, $\zeta_{harness}$ = 0.16; Best of all (K, $\zeta_{harness}$) tested

Table 6. Comparison of tandem cylinders to isolated cylinder $\zeta_{harness}$=0.16

U (m/s)	Harnessed power (Watts)			Ratio Two to single Isolated	Ratio Three to Isolated
	Single	Two	Three		
0.85	3.83	14.36	22.17	3.77	5.82
1.03	5.14	17.58	25.36	3.42	4.93
1.15	6.76	20.31	29.18	3.00	4.31
1.19	7.75	19.20	31.13	2.48	4.01
1.23	8.47	19.24	34.32	2.27	4.05
1.27	9.85	20.89	35.36	2.12	3.59

We have identified synergy and achieved η_{hydro} of 88% with 4 cylinders. So what?

Objective: *Achieve synergy w/o motion control*

III. 2ND GENERATION SUBSYSTEMS (1/6)

Objective: Portable, modular, easy to assemble

- Hydrodynamics: Achievable?
- Turbulence Stimulation: Slow flows
- Control: Oscillator properties not motion
- Magnetic Restraint: Counter drag/friction
- Magnetic Gear: Dry/wet environments
- Power Electronics: Signal conditioning
- Frame: Durable, easy to assemble & attach

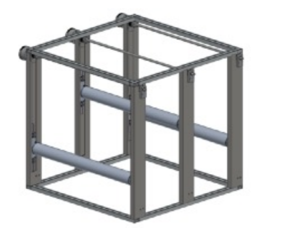


Fig. 1. 3-cylinder VIVACE-W

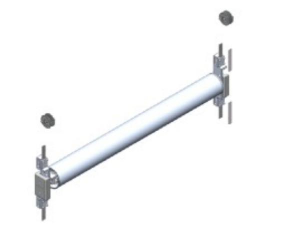


Fig. 2. Turbulence stimulation

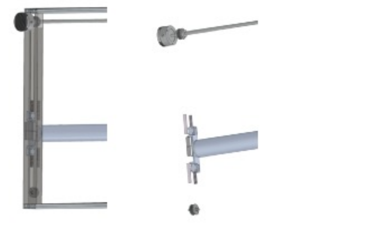


Fig. 3. Magnetic restraint & support

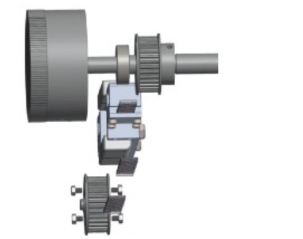


Fig. 4. Transmission: belt-sprocket-synch

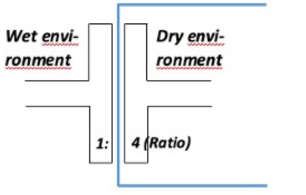


Fig. 5. Magnetic gear with wet/dry compartments

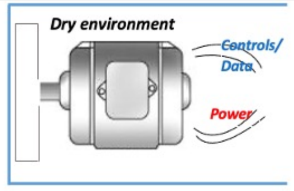


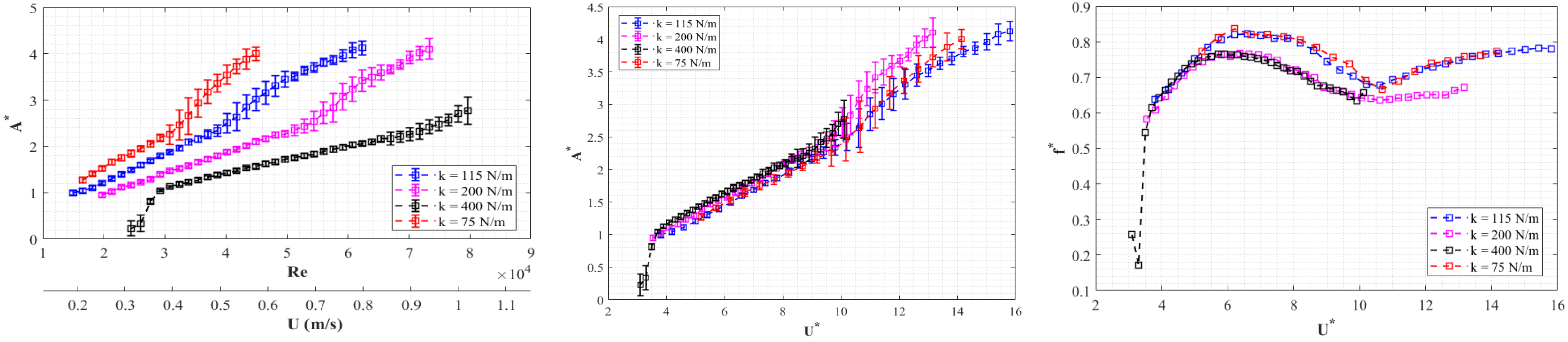
Fig. 8. VIVACE motor/generator. Oscillator property control.

$$P_{output} = \frac{1}{2}\rho v^3 L(D+2A) \bullet \eta_{Betz} \bullet \eta_{hydro} \bullet \eta_{support} \bullet \eta_{Vck} \bullet \eta_{transmission} \bullet \eta_{gear} \bullet \eta_{generator}$$

• $P_{fluid} = 0.59\frac{1}{2}\rho v^3 L(D+2A)$ • $\eta_{Betz} = 16/27$ • $\eta_{hydro} = \frac{P_{mech}}{P_{fluid}}$ • $\eta_{support}$ = contactless magnetic "levitation";

• η_{Vck} • $\eta_{transmission}$ • η_{gear} = contactless magnetic • $\eta_{generator} = \frac{P_{out}}{P_{mech}}$

Redesigned to harness energy even from ultra-slow flows (0.19m/s)



Effect of spring stiffness *K* for the *D*=8.89cm (3.5") cylinder with *H/D*=15 % and ζ_{total} = 0.04: (a) *A*=A/D* vs. flow speed *U* and Reynolds number *Re*, (b) *A*=A/D* vs. reduced velocity *U** (c) Frequency ratio $f^* = f_{osc}/f_{n,vac}$ vs. *U**

III. 2ND GENERATION SUBSYSTEMS (3/6): *Vck* controller

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

Vck

- Emulates spring stiffness ***k*** and damping ***c*** of any mathematical model linear or nonlinear and their parameters
- Enables quick change of oscillator parameters for testing or adaptation to excitation
- Enables use of the same physical equipment to harness energy from currents or waves
- Being redesigned to merge motor, generator, and controller for high η_{Vck}

III. 2ND GENERATION SUBSYSTEMS (4/6): Hydro-control

The challenge:

- VIV and galloping are naturally occurring instabilities and should not be controlled in the traditional sense
- Due to the high complexity of the hydrodynamics, there are many different phenomena that we have identified
- For traditional control or NN optimization a very dense database is needed
- There are numerous bifurcations between these phenomena
- Identifying all separatrices is practically prohibitive

  experimentally (even with the Vck)

  or with CFD (4-5 days for 60seconds simulation with 40 cores)

The solution:

- Instead of controlling the motions of the oscillators,

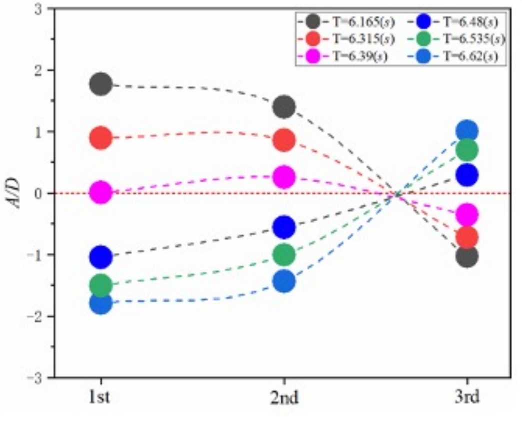
  design a closed-loop system, employing feedback control synthesis, implementing adaptive damping and stiffness that enable VIVACE-W to respond in oscillatory patterns mimicking fish undulation.

- These patterns match fish undulation modes!

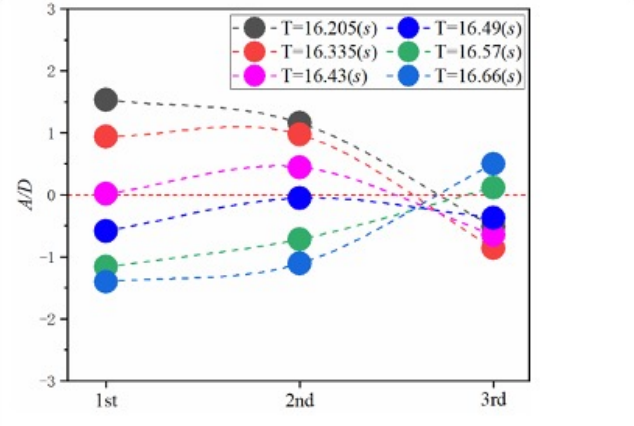
Method:

Instead of controlling the oscillator motions to mimic fish dynamics,
use adaptive oscillator properties
to enable the oscillators to precipitate into fish mimicking.

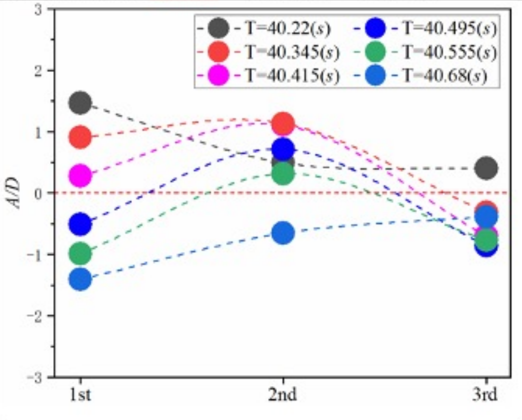
III. 2ND GENERATION SUBSYSTEMS (6/6): Hydro-control



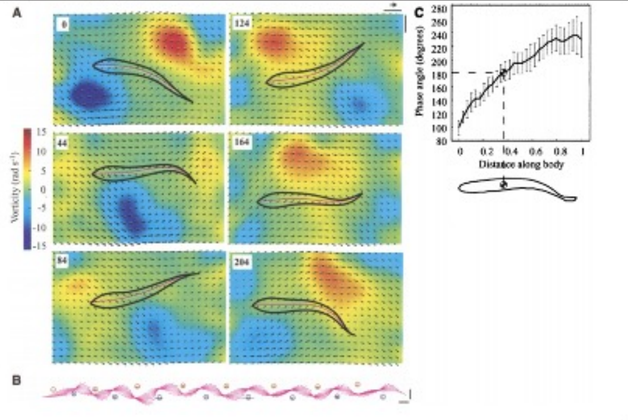
Positions of three tandem cylinders during half cycle of the first cylinder; L/D= 2.01, K=600N/m, $\zeta_{harness}$= 0.24, Re =114,000



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.



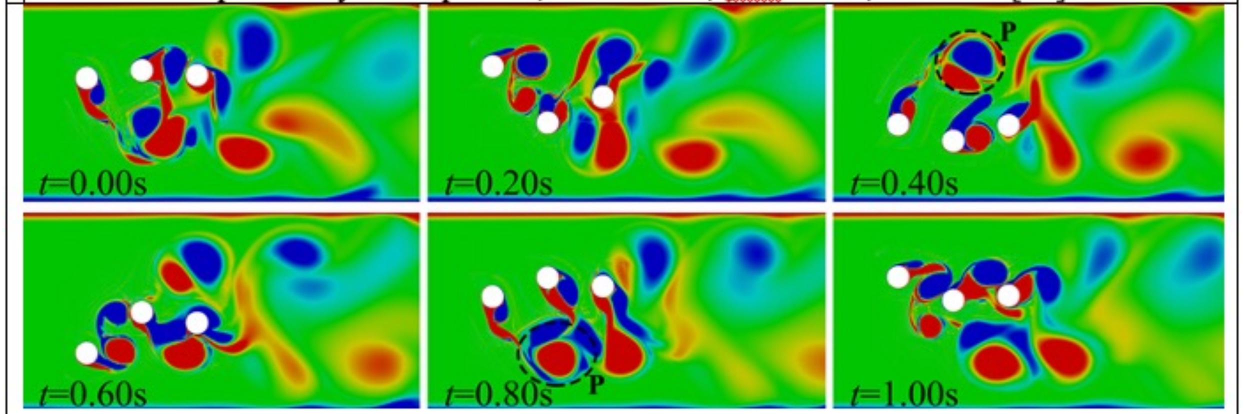
Positions of three tandem cylinders during half cycle of the first cylinder; L/D= 4.01, K= 600N/m, $\zeta_{harness}$ =0.24, Re= 114,000.



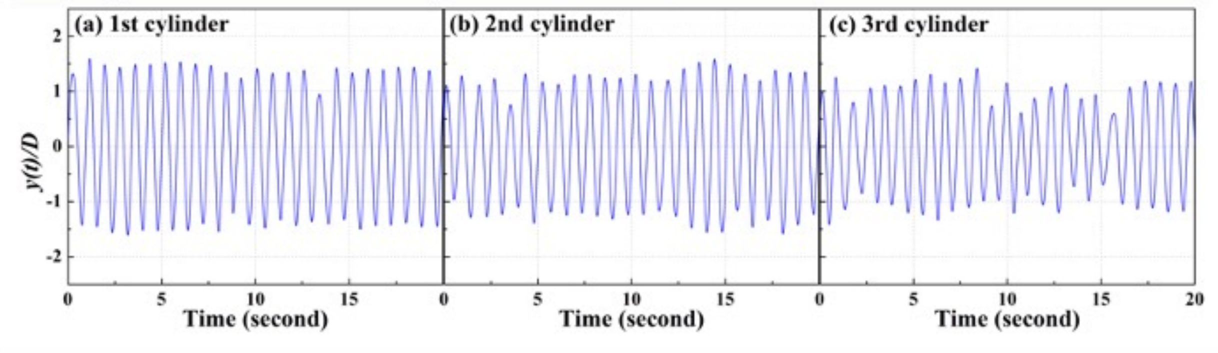
Interaction of trout with cylinder vortices

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, ζ_{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

CLOSING REMARKS

- The 1st generation VIVACE tested hydrodynamic concepts, fish friendliness, slowly moving parts, acceptance by communities, energy generation in V_{flow}=2-2.5knots

- The 2nd generation VIVACE is
  - portable, modular, easy to assemble
  - works even in ultra slow flows
  - enables high hydrodynamic efficiency w/o controlling oscillator motions
  - the *Vck* enables harnessing MHK energy from currents or waves
  - with adaptive damping, *the Vck*, makes the multiple oscillator VIVACE precipitate into high energy patterns which match fish undulation

Thank you for your attention and questions