Fluid-structure interaction problems in marine renewable energies

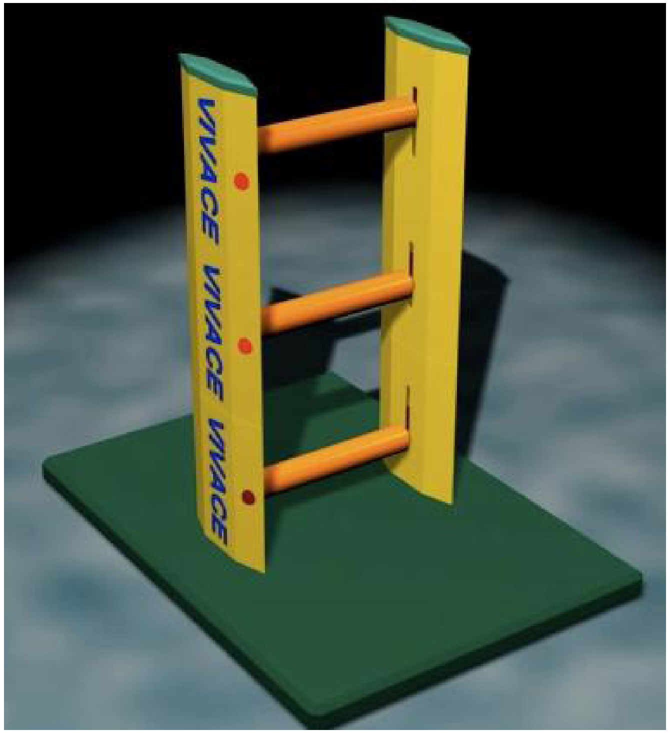
Lesson 3 : Using flow-induced vibration as an alternative to the propeller

Olivier Doaré
UME, ENSTA-Paristech
Olivier.doare (@t) ensta-paristech.fr

I – Galloping or VIV

Application

Application of the vortex-induced vibration and galloping phenomena



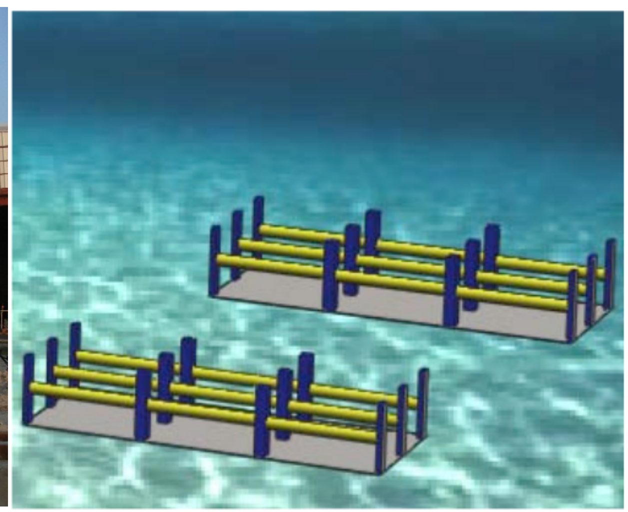
http://www.vortexhydroenergy.com/

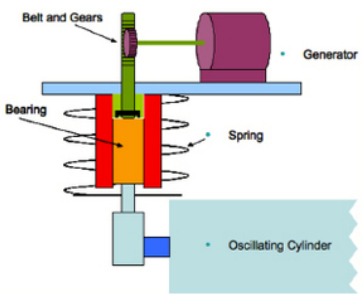
VIVACE project - University of Michigan - http://www.vortexhydroenergy.com/

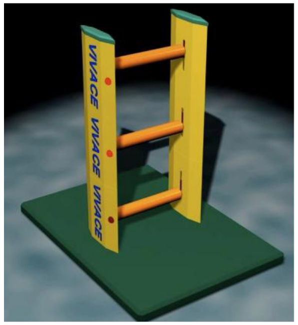
Multiple cylinders – Wake interactions

Cross-section optimisation
(to improve galloping)

Real world tests

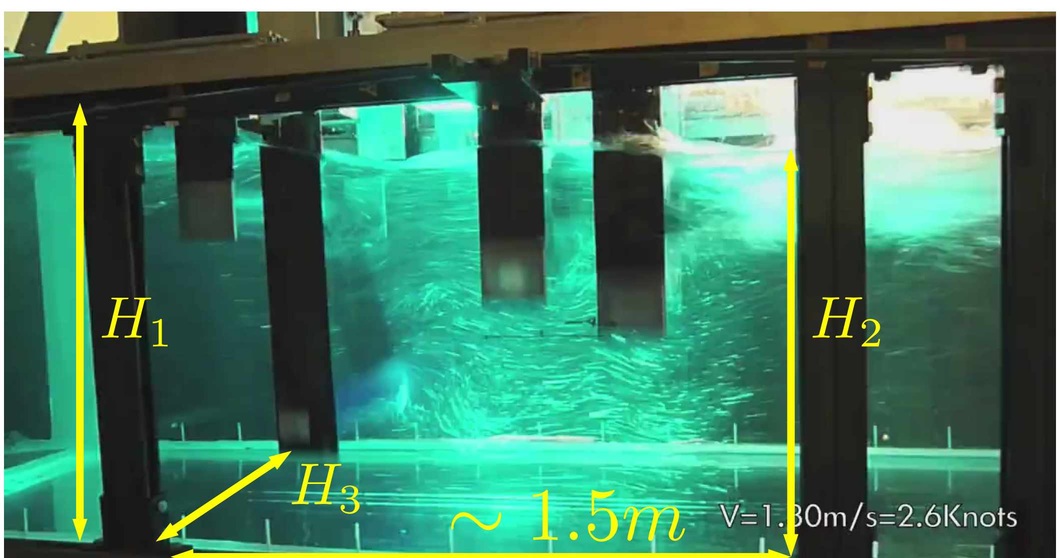






Power calculation on a real case

Exercise : Try to roughly estimate power removed from the flow by the system using only this movie and this image.



- River flow (flow rate= Q)
- Power flux = sum of kinetic and potential energies contributions
- To get the dissipated power by the system, we need the power upstream, and the power dowstream.
- Power of the river :

$$\Pi = \Pi_p + \Pi_k = \rho g Q h + \alpha \frac{\rho}{2} U^2 Q$$

$$\rho = 1000 kg/m^3 \quad U = 1.30 m/s$$

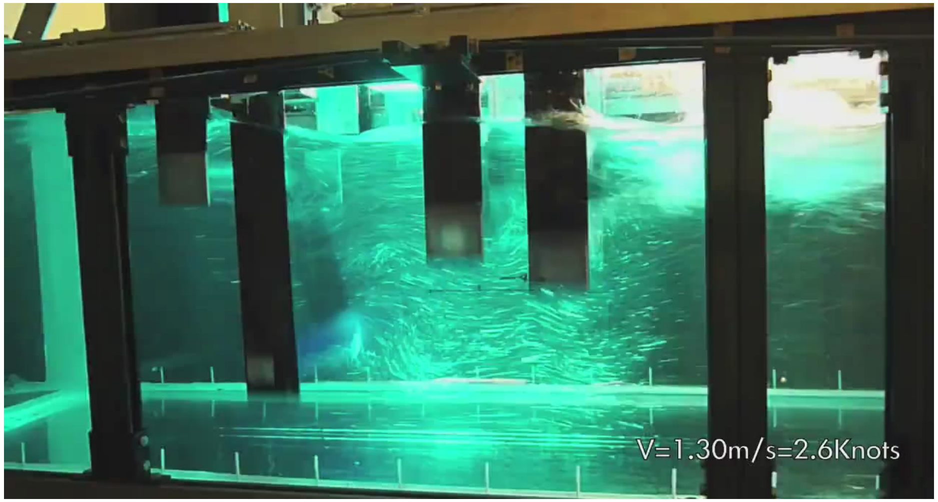
$$H_1 \sim 1m \quad H_2 \sim 0.85m \quad H_3 \sim 1m$$

$$\Pi_{p1} \sim 13kW \quad \Pi_{k1} \sim 1.1kW$$
$$\Pi_{p2} \sim 11kW \quad \Pi_{k2} \sim 1.5kW$$

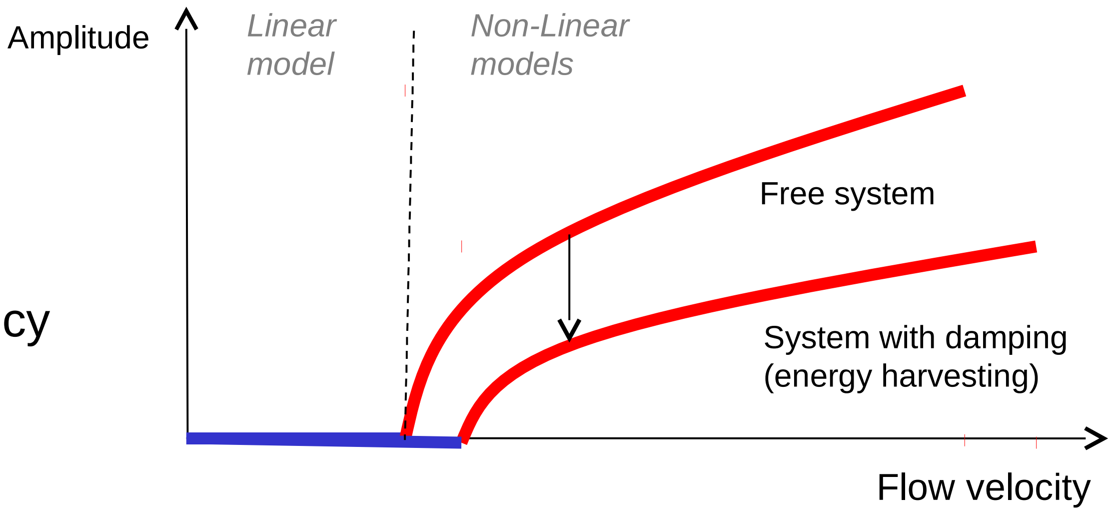
$$\Delta\Pi \sim 1.6kW$$

Okay, but...

1 - Where is this going all this energy ?

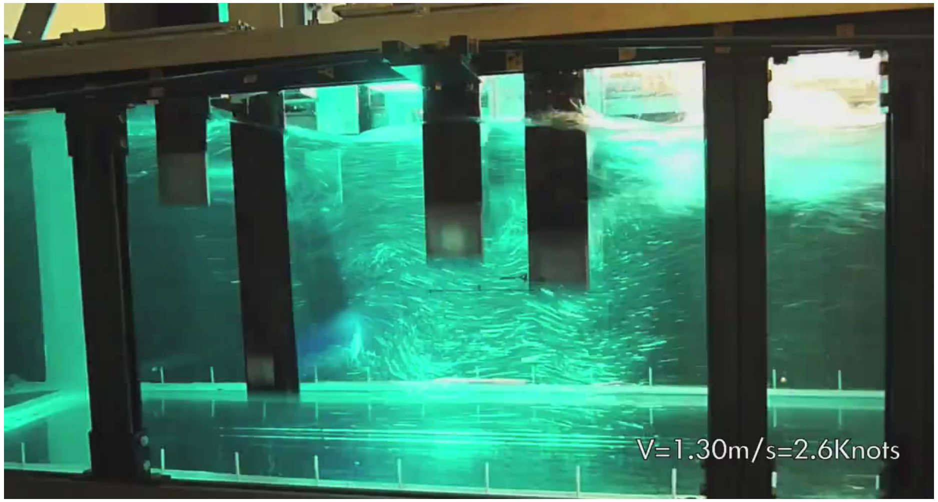


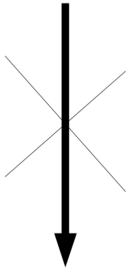
- Dissipated in the flow
- Dissipated by friction
- If we try to further get energy
  → additionnal damping
  → lower amplitude, lower efficiency

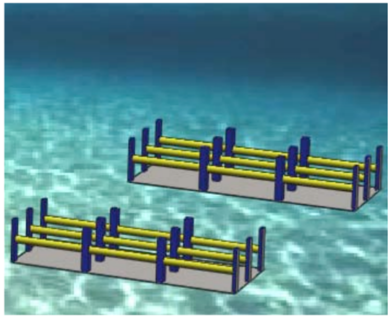


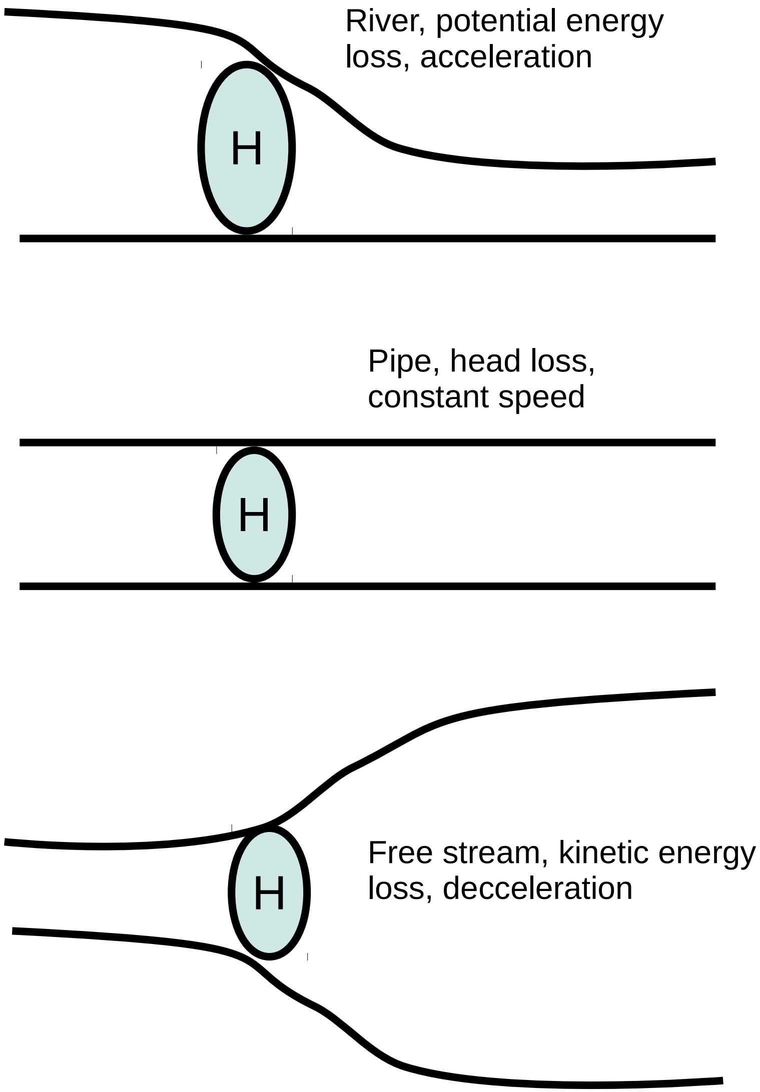
Okay, but...

2 - What happens if the system is not put in a river ?



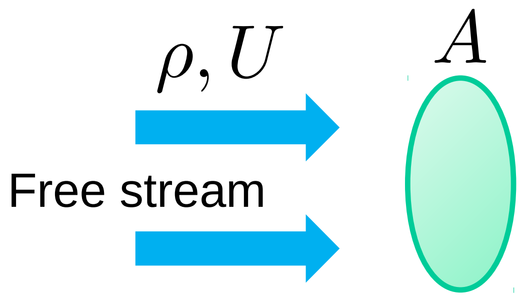






Various efficiency definitions

- In the previous example, we don't know if and how energy is converted
- In energy harvesting studies we generally use a classical windmill efficiency :



$$\Pi_i = \frac{1}{2}\rho A U^3 \equiv \text{Incident power}$$

$$\eta = \frac{\Pi}{\Pi_i} \equiv \text{Efficiency}$$

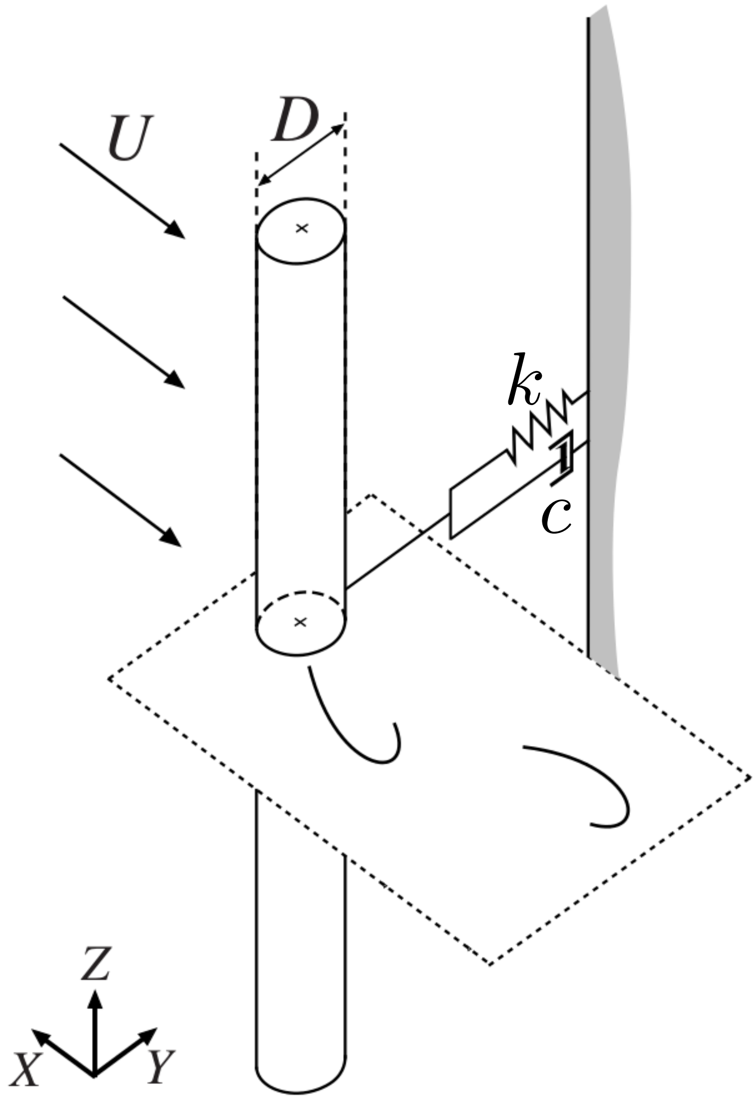
- Different definitions of power Π :

$\Pi_T \equiv$ Total power lost by the mean flow ← Betz law (free stream!) $\eta_{Tmax} = \frac{16}{27}$

$\Pi_D \equiv$ Total power dissipated by the (electro)mechanical system ← Often used for windmills

$\Pi_C \equiv$ Power converted (useful power) ← « Real » efficiency

Example of efficiency optimisation work on VIV



- Single oscillator with a damping term modeling the energy harvesting

$$m\ddot{x} + (c + c_a)\dot{x} + kx = \chi q$$

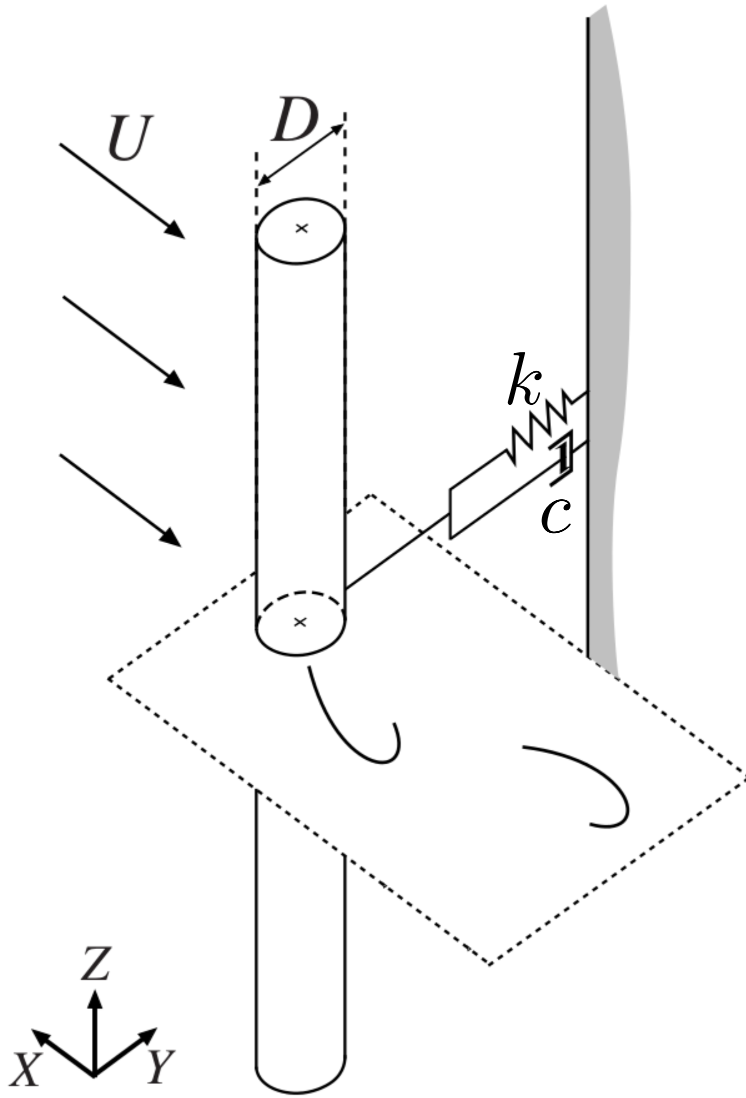
- Fluctuating lift introduced through a wake oscillator model

$$\ddot{q} + \epsilon(q^2 - 1)\dot{q} + q = \alpha\ddot{x}$$

- Efficiency defined as the ratio between the mean power dissipated in the damper and kinetic energy flux in a cross-surface occupied by the oscillating cylinder.

$$\eta_D = \frac{\langle c_a \dot{x}^2 \rangle}{\frac{1}{2}\rho D U^3}$$

(Facchinetti et. al, 2004 ; Grouthier et. al, 2012)

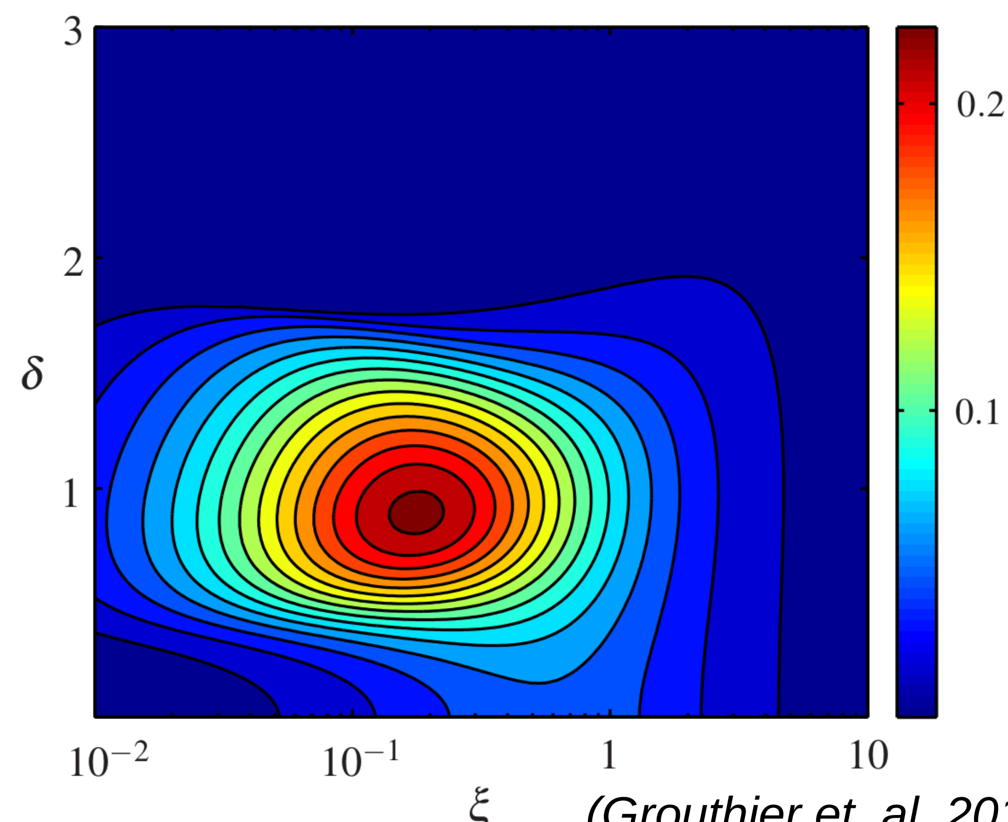


- Most of the coefficients may be fixed by fitting experimental results of VIV.
- Two parameters left to be varied :

$$\delta = \frac{\omega_s}{\omega_f} \qquad \xi = \frac{c_a}{m\omega_f}$$

- Efficiency :

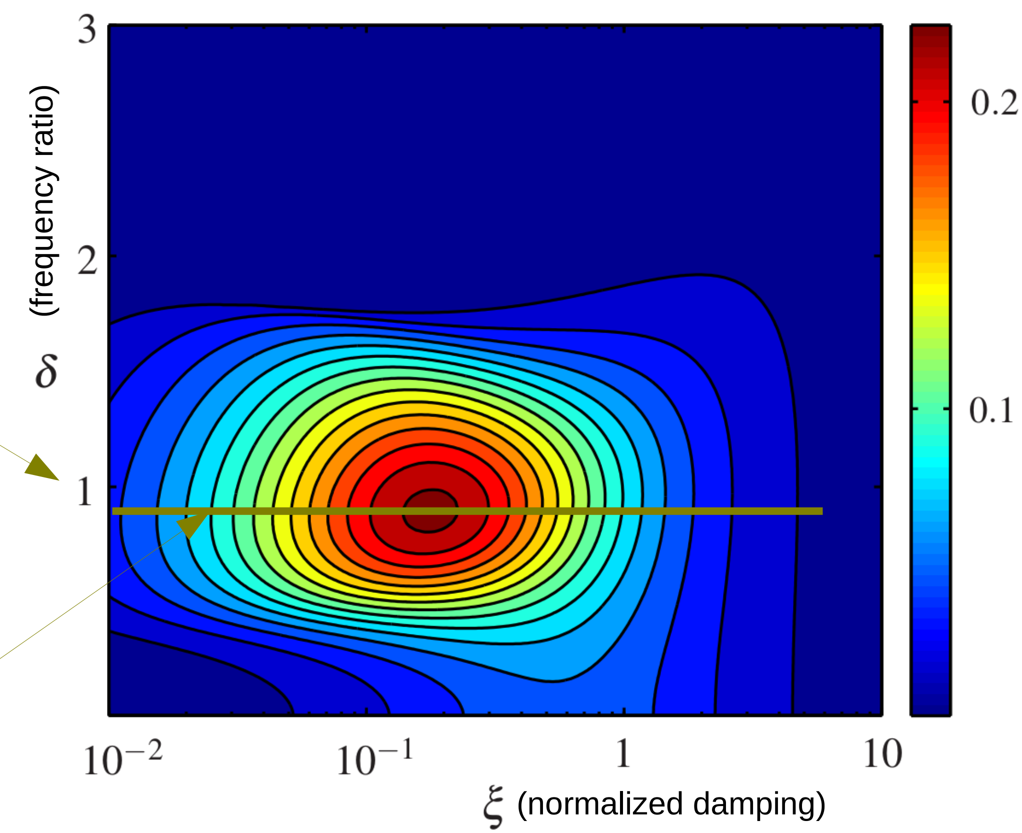
$$\eta_{Dopt} = 0.23$$

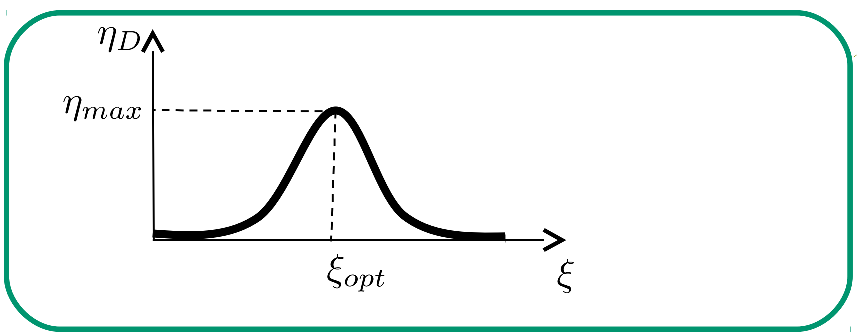


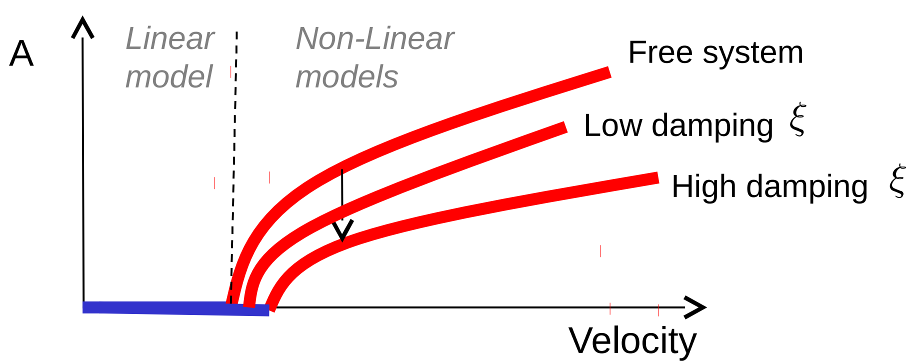
(Grouthier et. al, 2012)

Optimal efficiency

Optimal efficiency when wake oscillator and mechanical oscillator are synchronized



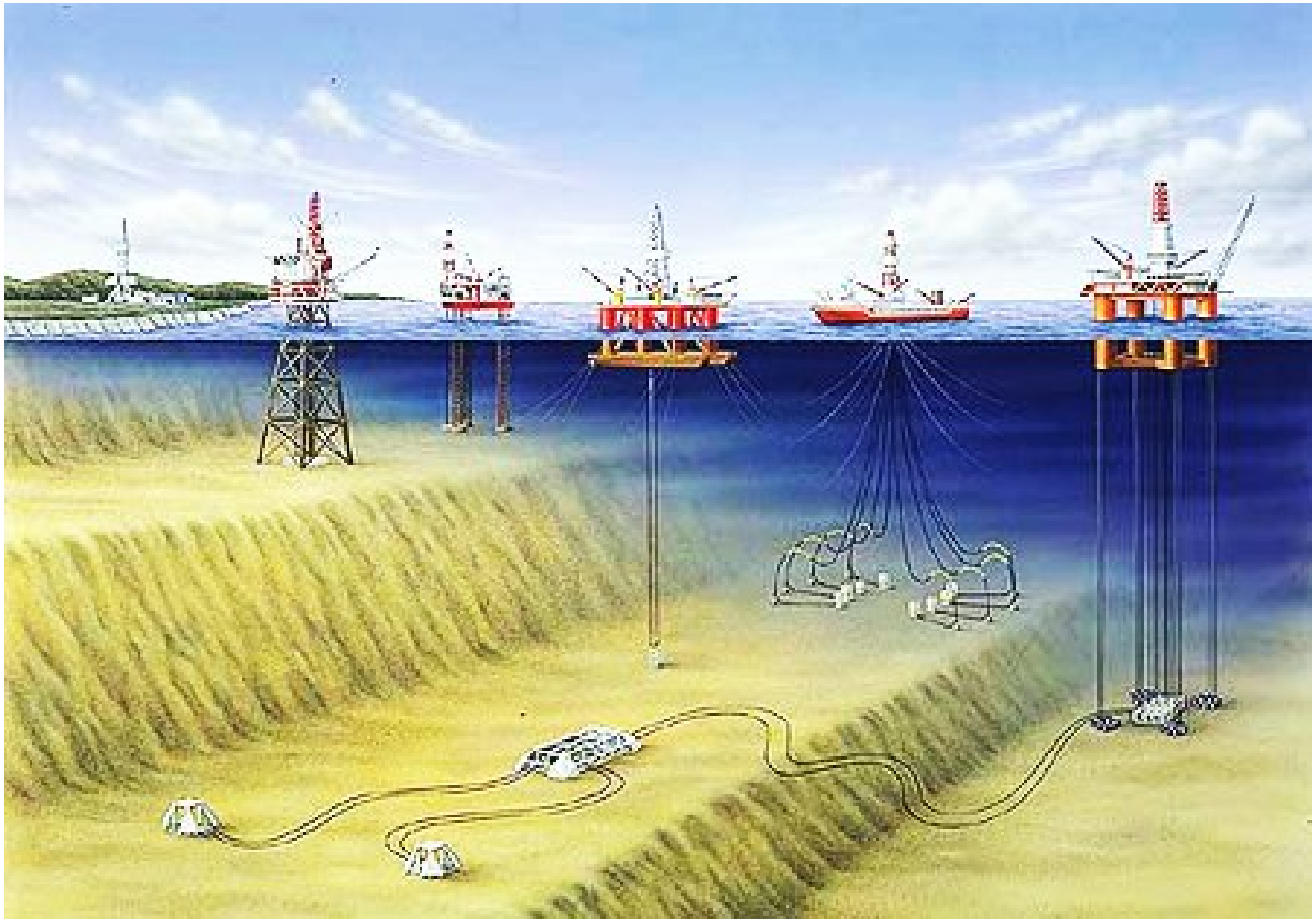




$$\eta_{Dopt} = 0.23$$

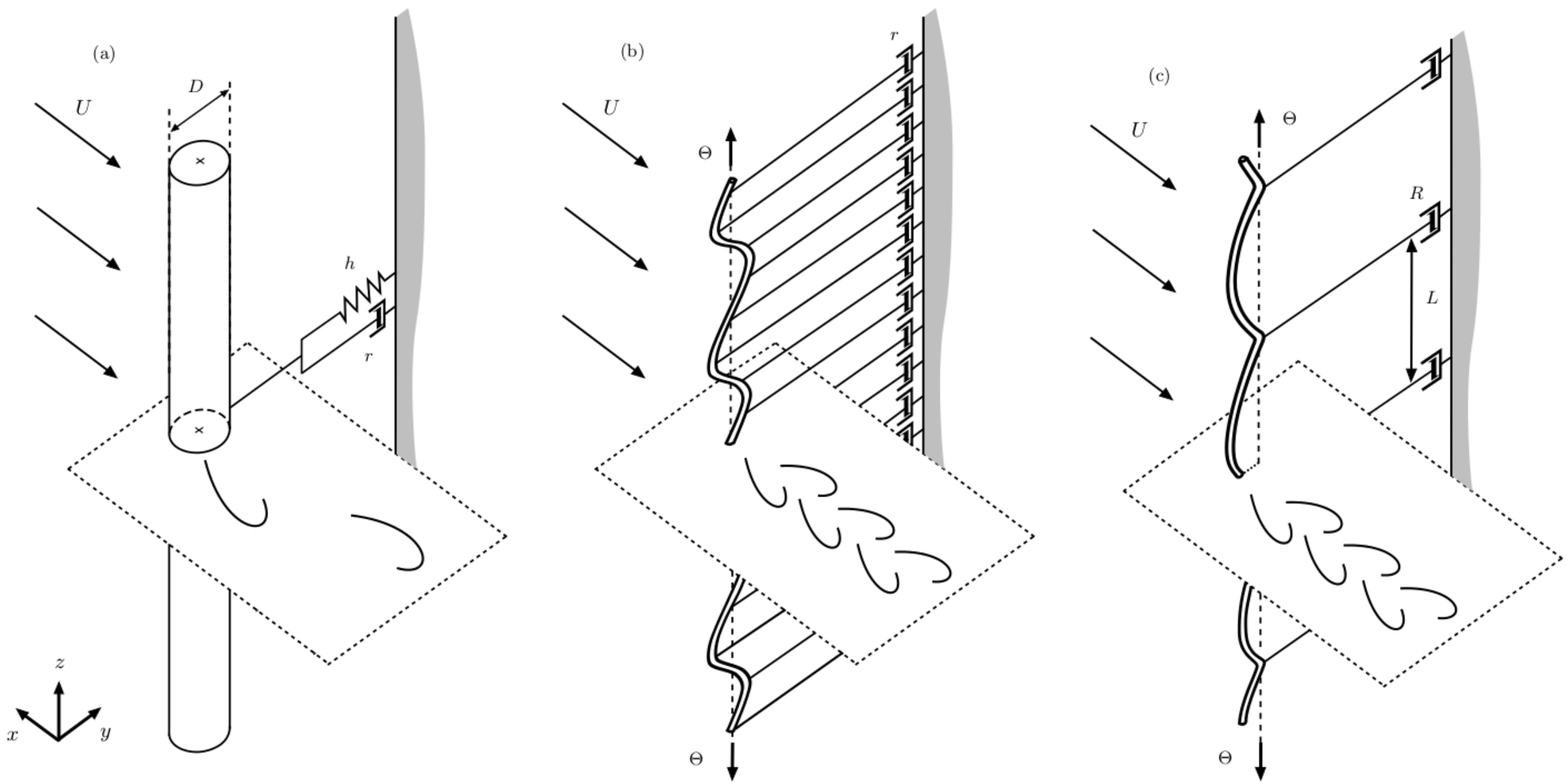
(Grouthier et. al, 2012)

Taking profit of ambient vibrations



VIV are encountered on thousands meters cables in the offshore industry !

Waves along cables coupled to VIV



Discrete oscillator coupled to a damper

Cable coupled to a continuous series of dampers

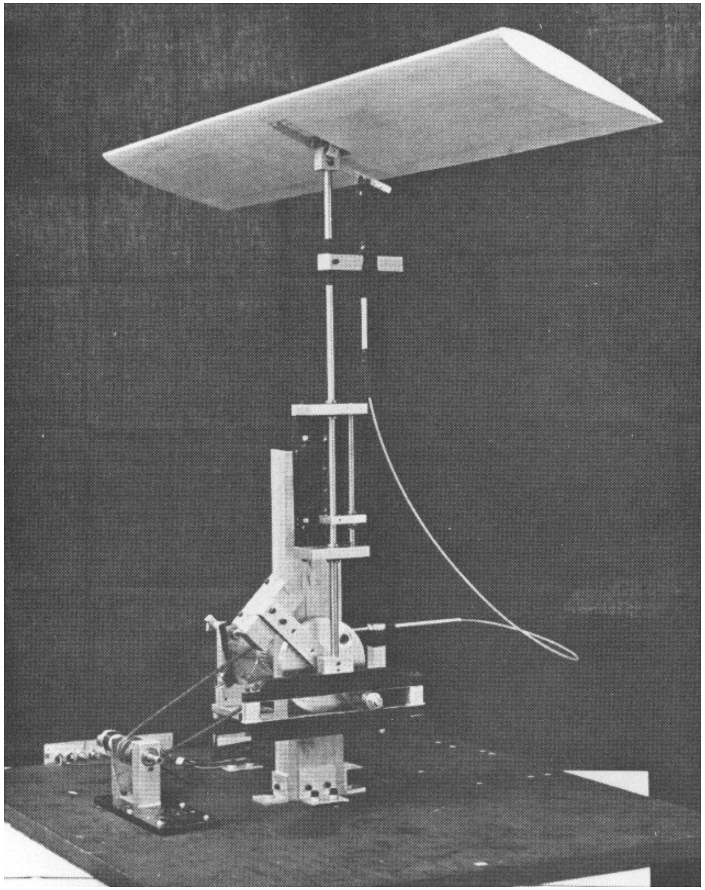
Cable coupled to a discrete series of dampers

(Grouthier et. al, 2012)

2 - Wing flutter generator

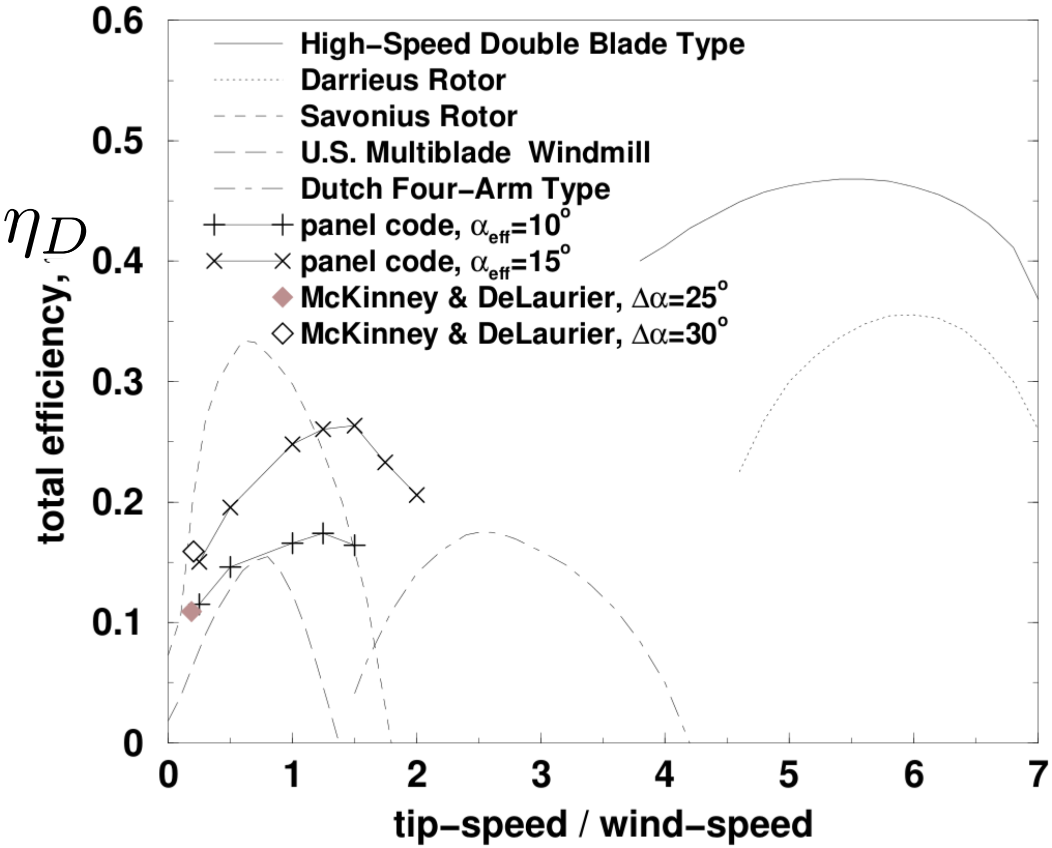
Applications

First wingmill prototype by McKinney and DeLaurier (1981)



(McKinney and Delaurier, 1981)

- One degree of freedom system
- The pitch is slaved to the plunge
- Phase difference between pitch and plunge can be tuned to select the optimal efficiency



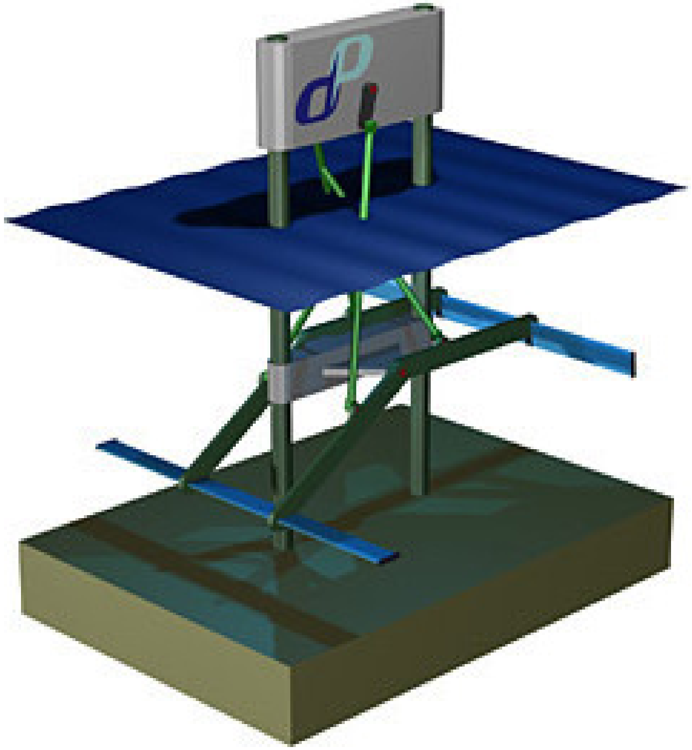
(Jones et. Al, 1999)

Some commercial products

The STINGRAY project (Engineering Business Ltd.)

- Experimental project of the early 2000's
- 15m span 3m chord, displacement amplitude of 12m
- Displacement of the wing transmitted to an hydraulic motor through hydraulic cylinders
- Abandonned project because of economic viability

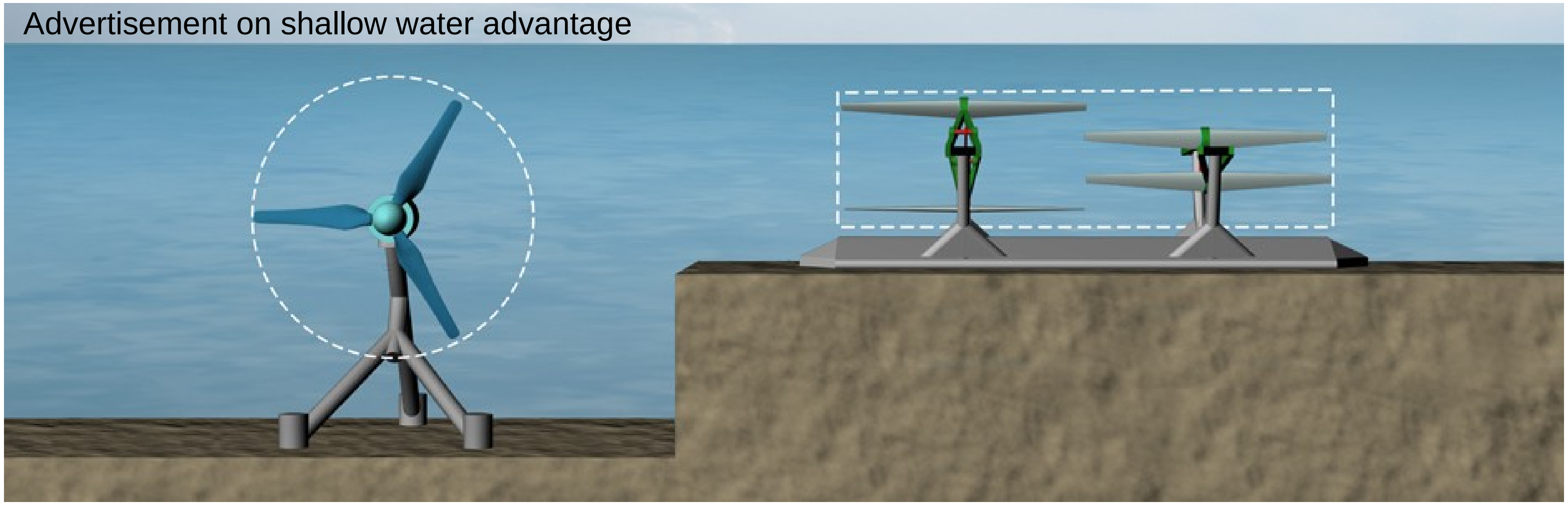
Some commercial products

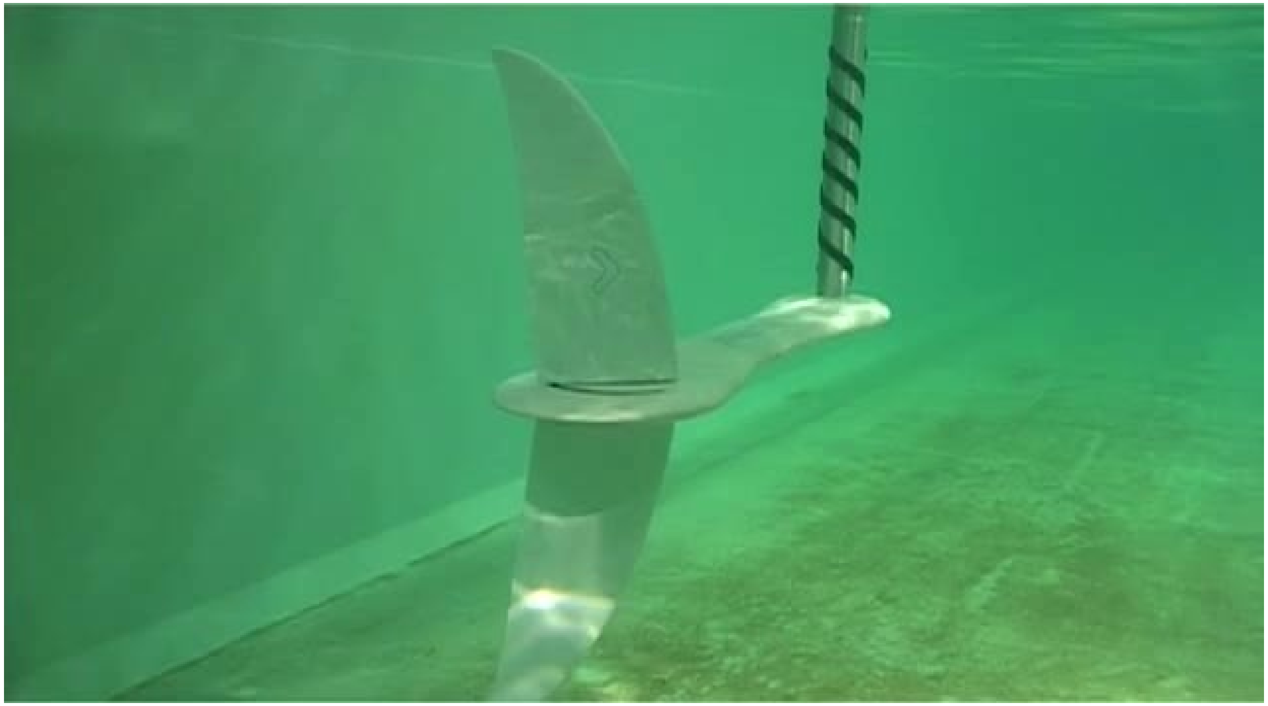


Pulse Generation

PULSE-TIDAL

- Two wings are phase-locked, translation and rotation of each wing also phase-locked
- Movement transitted to a generator through arms
- Generator can be put in or out the water
- Small vertical space



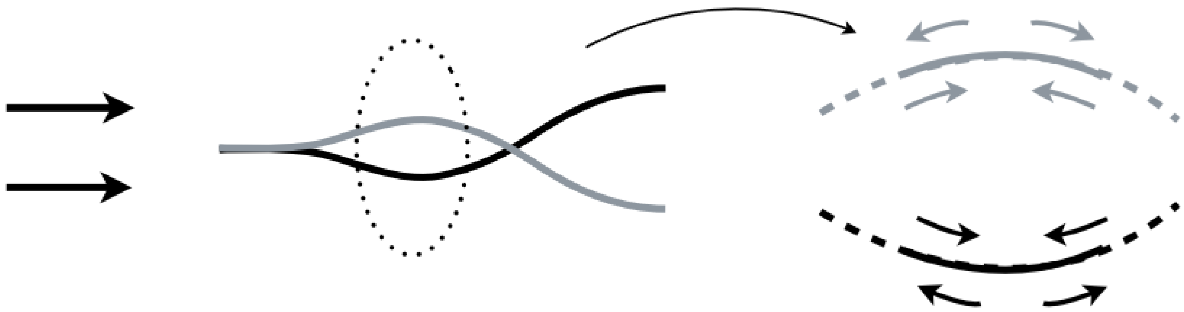


http://www.biopowersystems.com/biostream.html

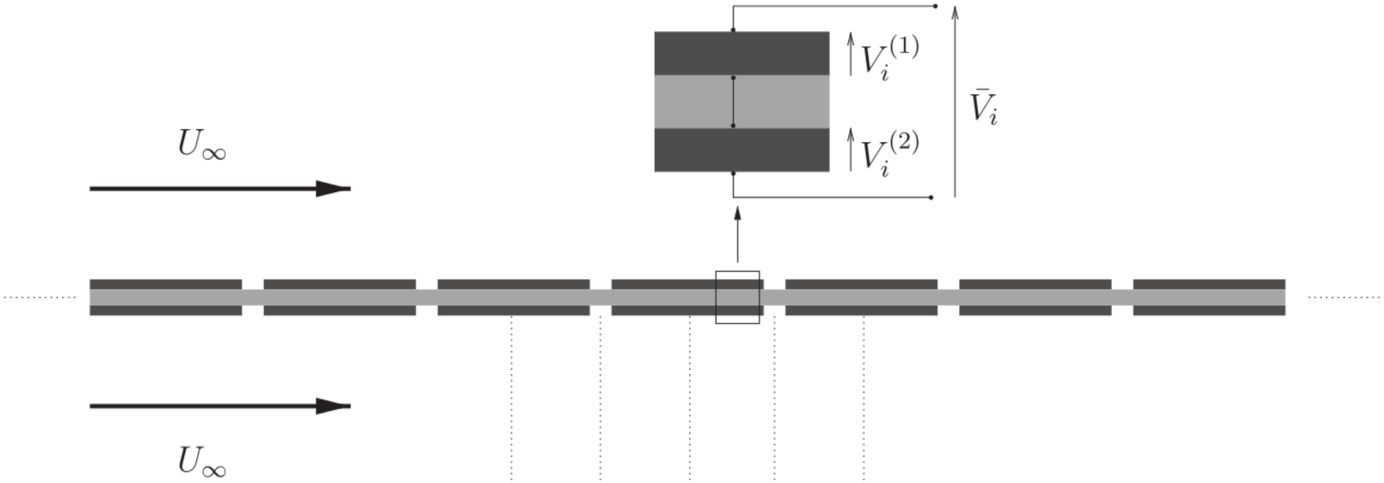
3 - Flag flutter generator

Use of flag flutter : Introduction of a converter, piezoelectricity

Plate flutter results in stretching and compression of the material

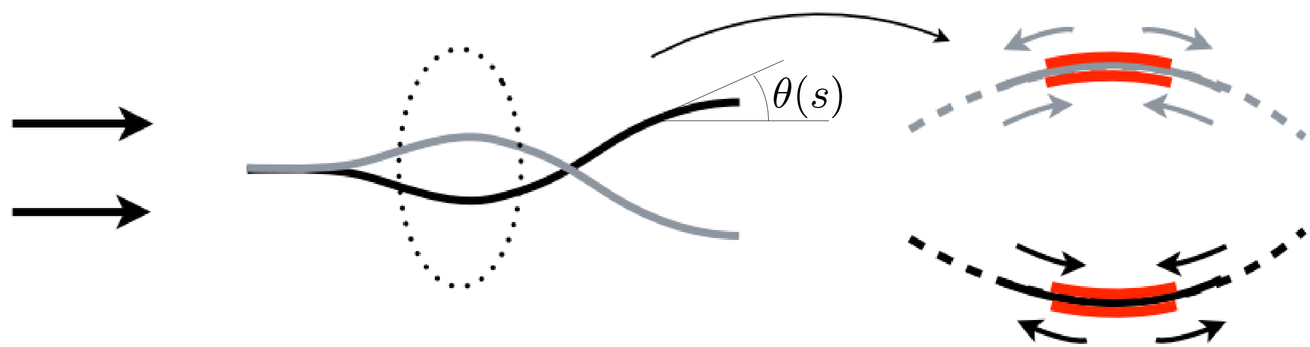


Idea : put a series of piezoelectric patch pairs on the plate to convert bending to electric potential



(Doaré & Michelin, 2011)

Complete and explicit description of the fluid-solid-electric coupling



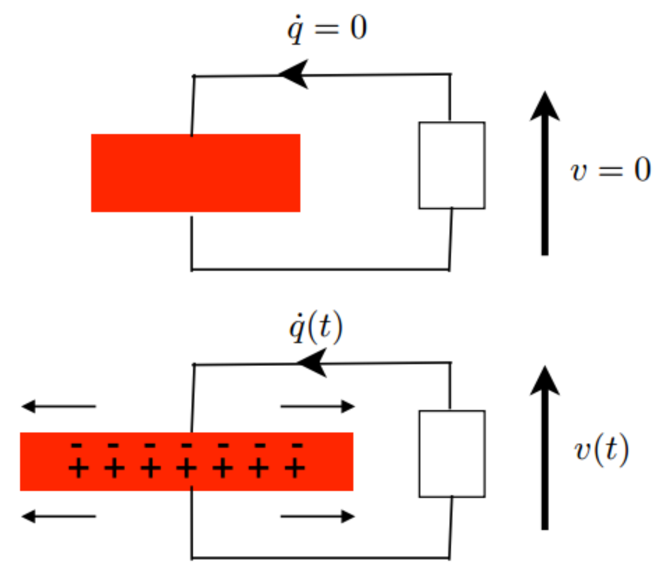
Piezoelectric couplings (long wavelength approx.) :

- Flapping motions → piezoelectric stretching/compression
  → electric charge transfer

$$q = cv + \chi \frac{\partial \theta}{\partial s}$$

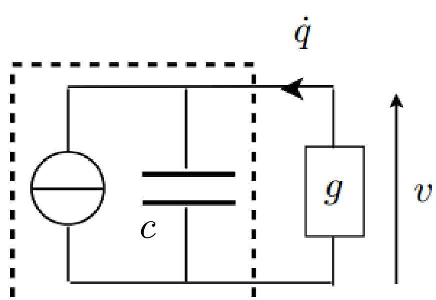
- Voltage at the outlets → local torque on the beam

$$\mathcal{M} = -\chi v$$



Electrical model :

$$\Pi_C = \int_0^L g v^2 ds$$

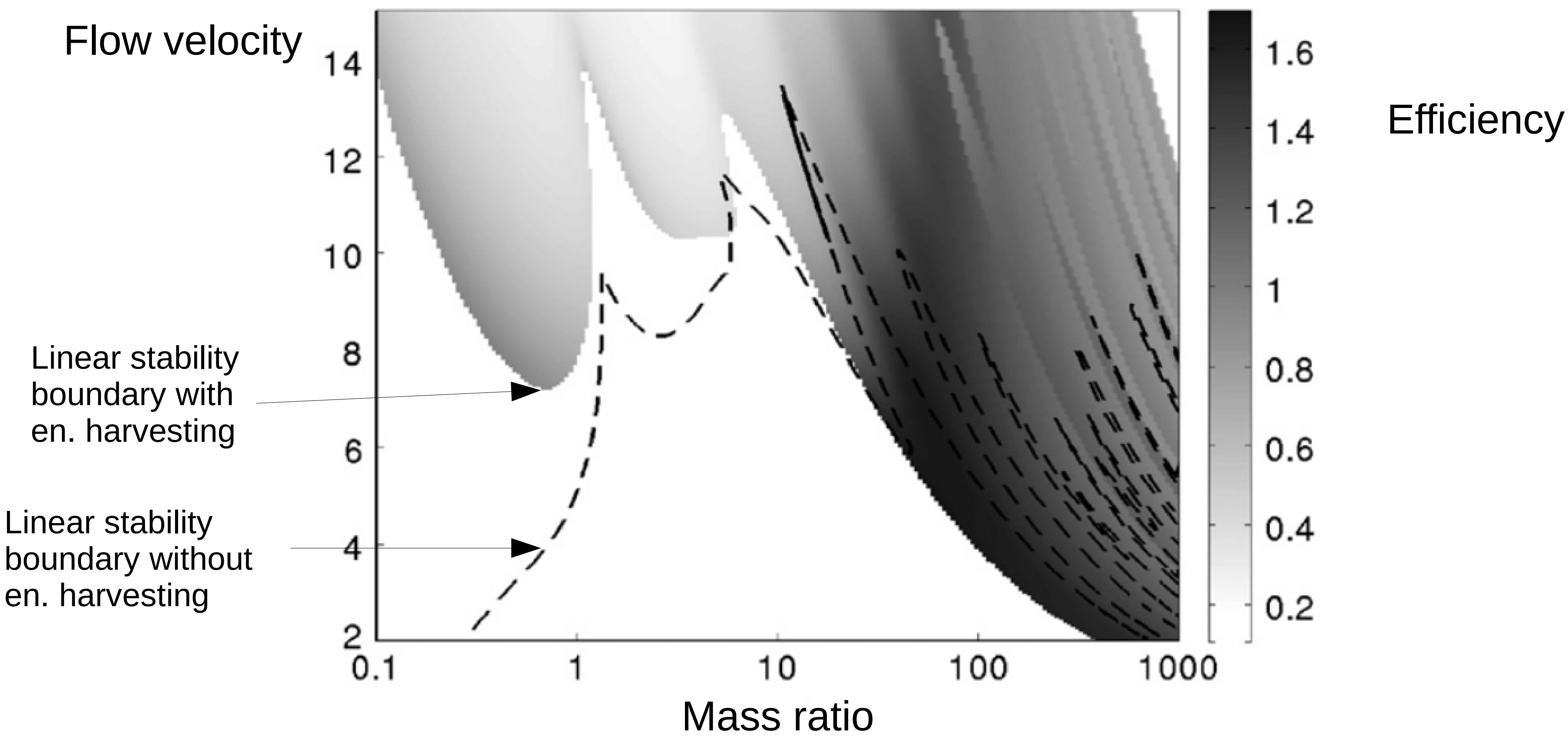


+ Nonlinear fluid-solid model

(Doaré & Michelin, 2011 ; Michelin & Doaré, 2013)

Linear stability and efficiency analysis

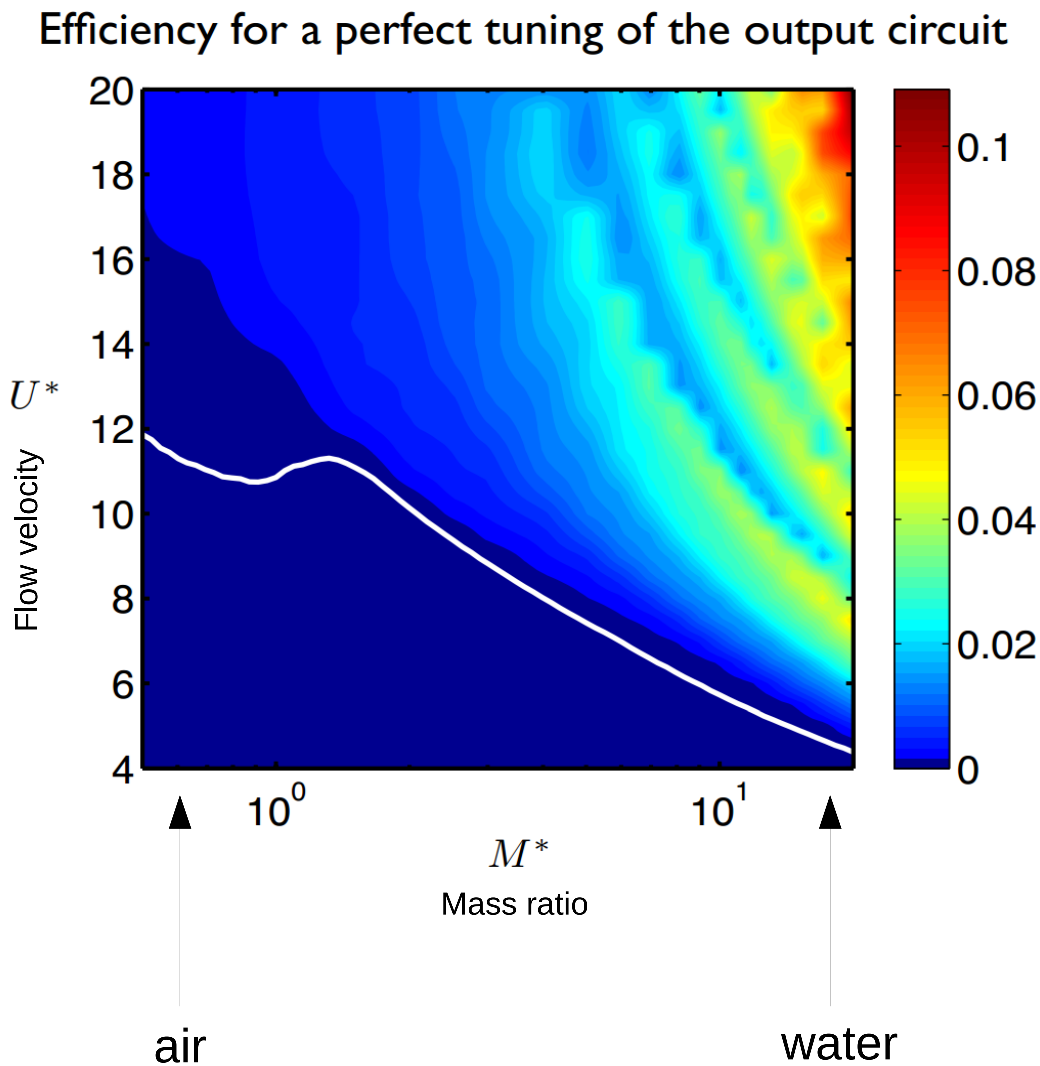
$$\text{Linear efficiency} = \frac{\text{Energy dissipated by he electrical system during one period}}{\text{Mean value of the kinetic and potential energies in the system}}$$



- Energy harvesting may destabilize and thus improve the fluid-solid coupling
- Phenomenon associated to negative energy waves
- Efficiency is maximum when destabilization occurs

(Doaré & Michelin, 2011)

A case of real efficiency optimization (nonlinear modeling)



(Michelin & Doaré, 2013)

- A significant amount of power can be harvested if the system is correctly tuned

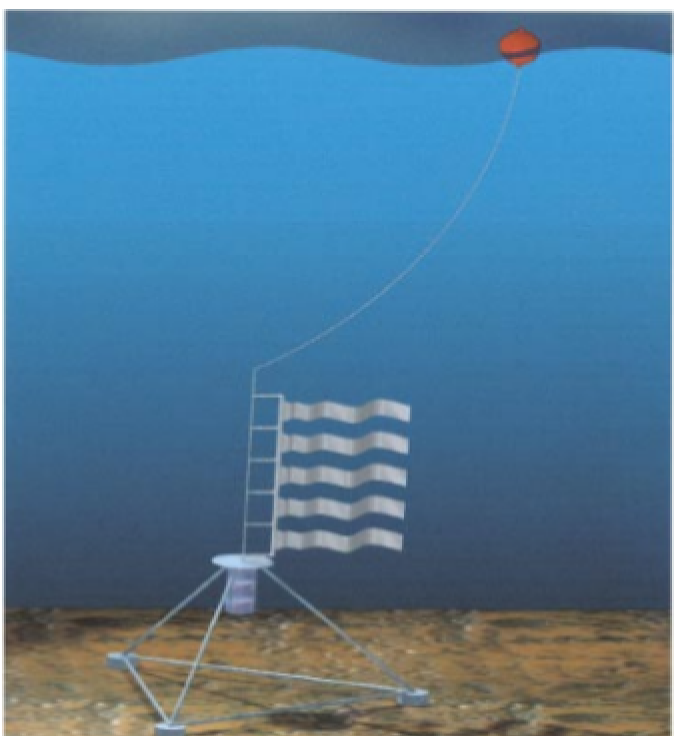
- **Improvement 1** : Use of active circuits, resonant circuits (huge scientific litterature in the field of power electronics).
- **Improvement 2** : Consider multiple harvesters, hydrodynamic and electric interactions
- **Improvement 3** : Find optimal distributions

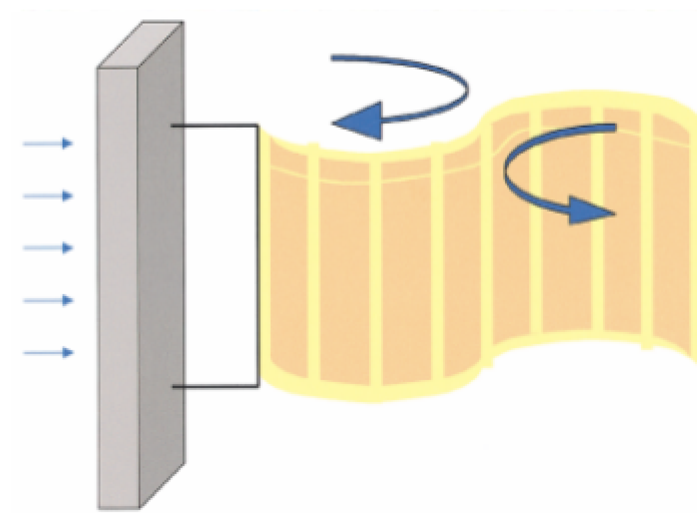
- **Problem 1** : Probably not suited for large scale energy conversion
- **Problem 2** : Highly dependent on the piezoelectric coupling of the material

- Good for small scale systems : power autonomous sensors

Conclusion on axial flow instabilities

- Ongoing researches to estimate the optimal efficiency of such systems
- Encouraging results on piezoelectric plates but application may be very challenging
- Many other researches, involving other harvesting principles (eg. pure dampers, Induction)





Proposed prototype by *Taylor et al (2001)*

Conclusion

- Various physical mechanisms are able to transfer flow energy to a structure
- Efficiency calculations have been presented (~ 0.1 – 0.3)
- Efficiency of some systems are encouraging but remain lower than the best systems involving a propeller
- Still a lot of research work to do, some promising industrial applications