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Hydrokinetic Energy Conversion: Some CFD Contributions to the Development of Turbine Technologies and their Deployment in Arrays

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CFD Laboratory LMFN

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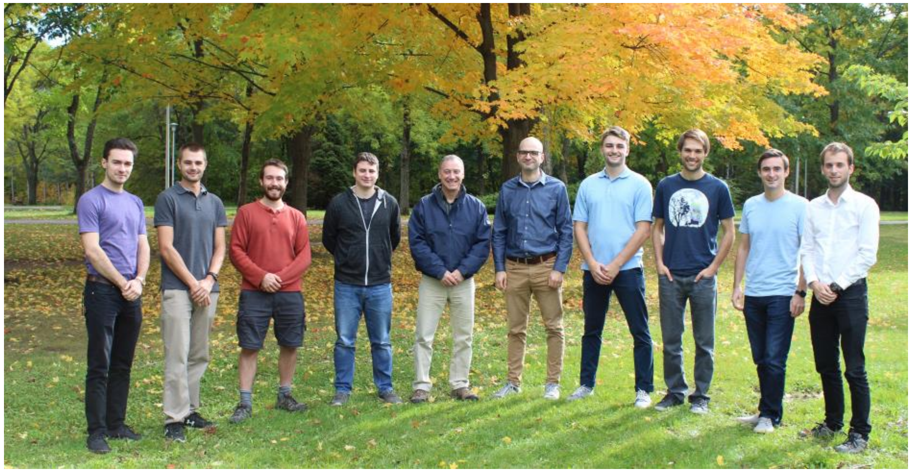
Natural Resources Canada (NRCan), National Research Council of Canada (OCRE Group)

LMFN



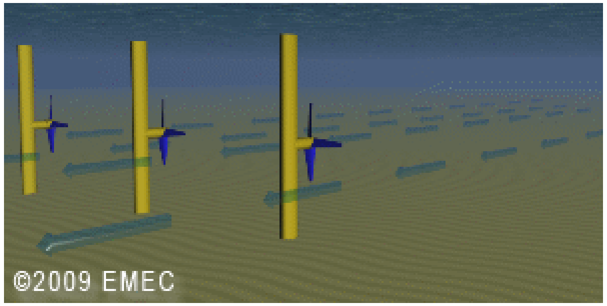
Tidal and river hydrokinetic turbines

Three main types of turbine technologies

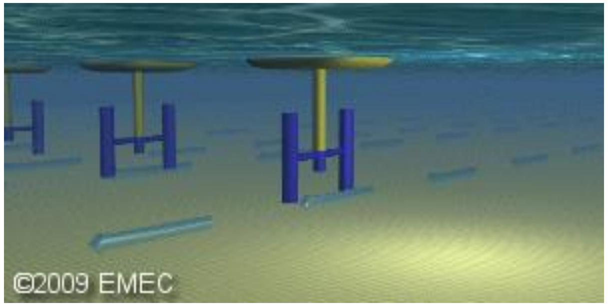
- Typically designed and optimized **while operating in isolation and under clean inflow conditions**

Can be deployed in arrays to maximize energy output from a given site

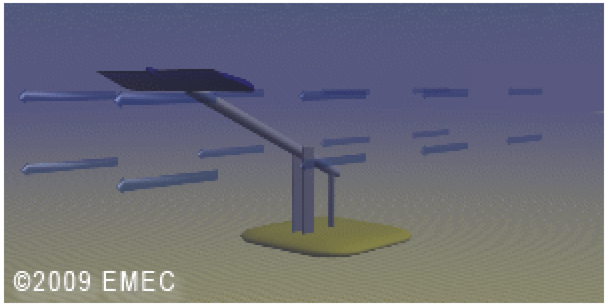
- **Blockage effects, turbine-wake interactions, perturbed flow conditions**



Axial-**F**low **T**urbine



Cross-**F**low **T**urbine

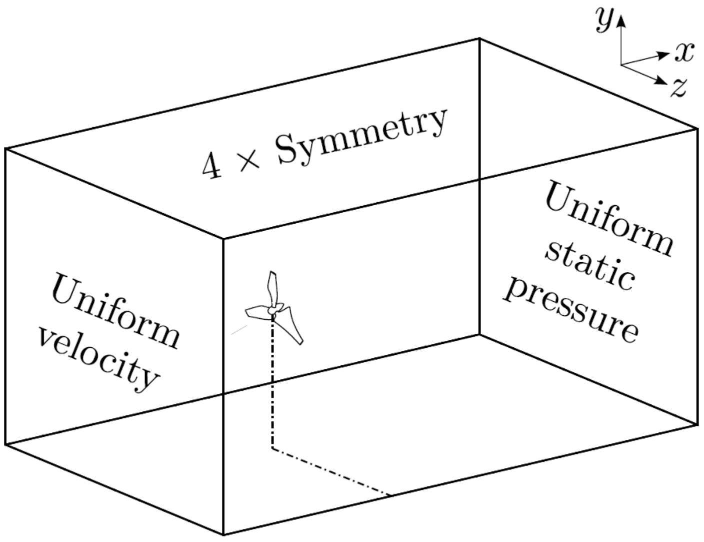


Oscillating-**F**oil **T**urbine

Full-Rotor CFD Simulations

Isolated turbine - Performance prediction

- Commercial finite-volume solvers:
  ANSYS-Fluent (moving mesh, generalized interfaces, non-inertial reference frame, …)
  Star-CCM+ (overset meshes)
- **High Reynolds number**:
  $Re = U_0 D / \nu \approx 10^7$
- Unsteady RANS simulations (**URANS**)
- Turbulence models:
  Spalart-Allmaras; k-ω SST; **y+ ≈ 1 on blades**
- **Clean inflow conditions**:
  uniform velocity, low turbulence level
- **Large, unconfined domain (no free-surface)**:
  10D upstream, 20D downstream
  Blockage ratio: $B = A_{turb}/A_{channel} < 0.5\%$
- Second-order space and time discretizations



- 1000-2000 timesteps / cycle
- Performance metrics averaged over 5-10 cycles

Full-Rotor CFD Simulations

Isolated turbine - Per

- Commercial finite-volume solv
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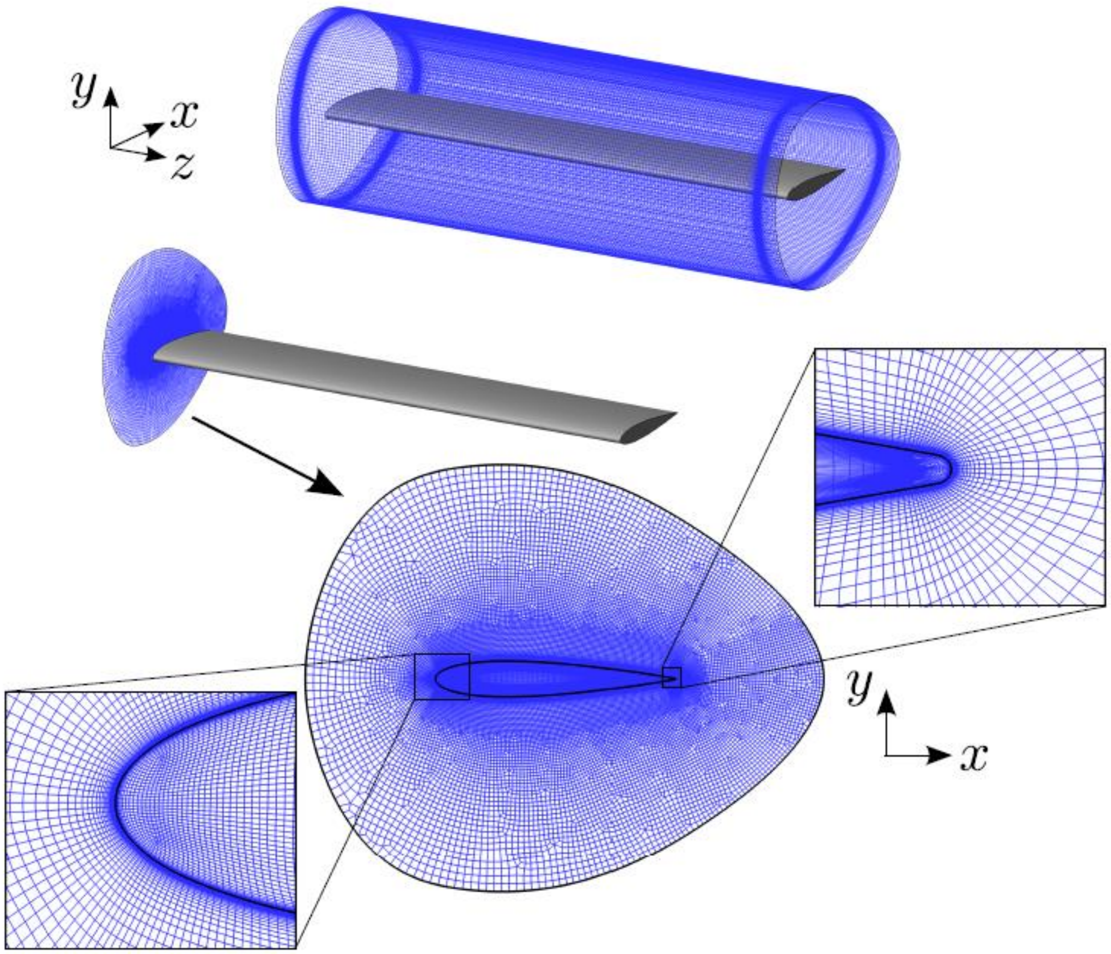
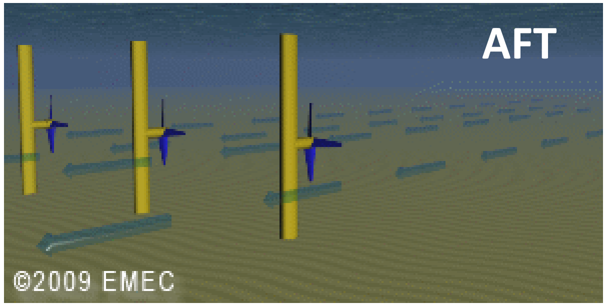
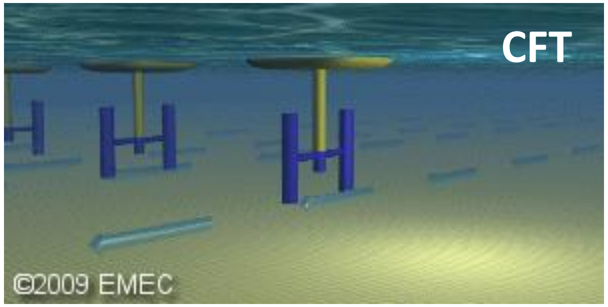
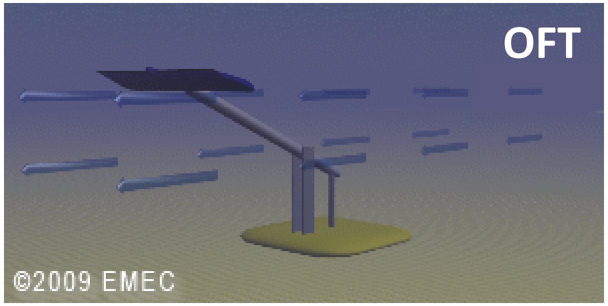


Moving mesh region of the OFT case.

Tidal and river hydrokinetic turbines







Axial-Flow Turbine

- Efficient turbine concept ($\eta \approx 45\%$)
- Blades operate in stationary hydrodynamics
- Constant torque and power production
- Circular harvesting plane limits power in shallow water applications (high-speed flows)

$$P = \eta \times \frac{1}{2} \rho U_\infty^3 A$$

CFT and OFT

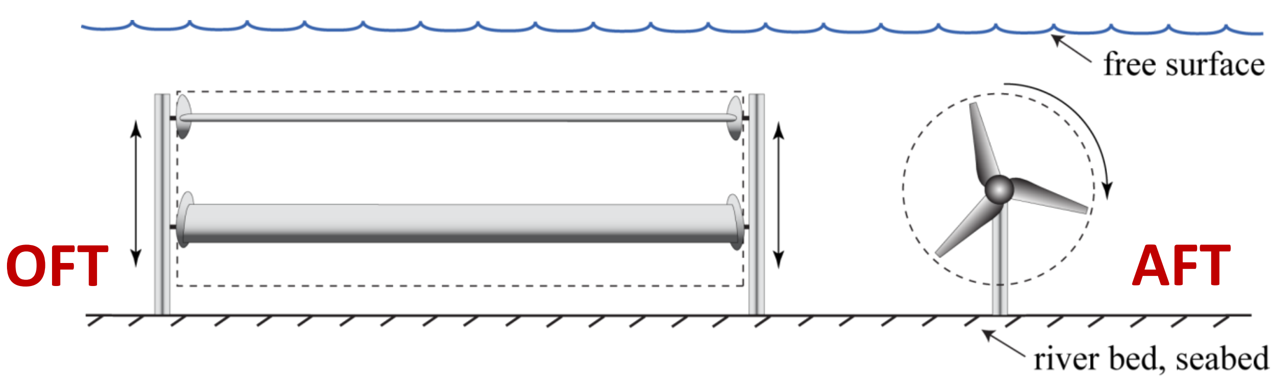
- Blades operate in unsteady hydrodynamics
- Benefit from potentially larger instantaneous force coefficients
- Better adapted to shallow waters when deployed horizontally

Rectangular Harvesting Planes

$$P = \eta \times \frac{1}{2}\rho U_\infty^3 A$$

A = frontal area

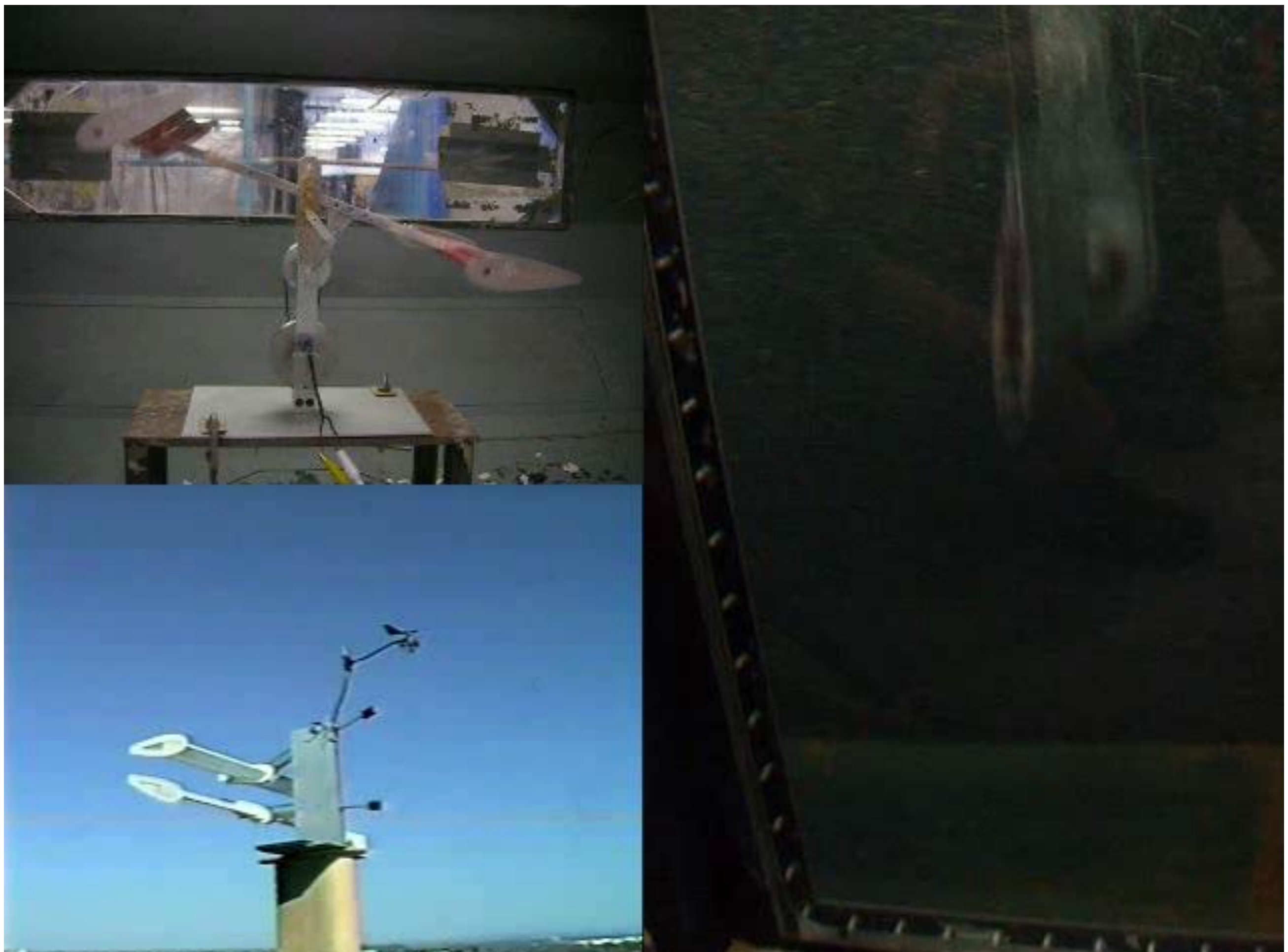
$A_{AFT} << A_{OFT}$



- **Rectangular extraction plane** well-suited to river and sea beds and to shallow waters near the coastline
- **Power scalable** even in shallow waters (increase A with blade span)

Oscillating-foil turbine

- Benefit from unsteady flow dynamics
  - → **Higher angles of attack → Larger forces**

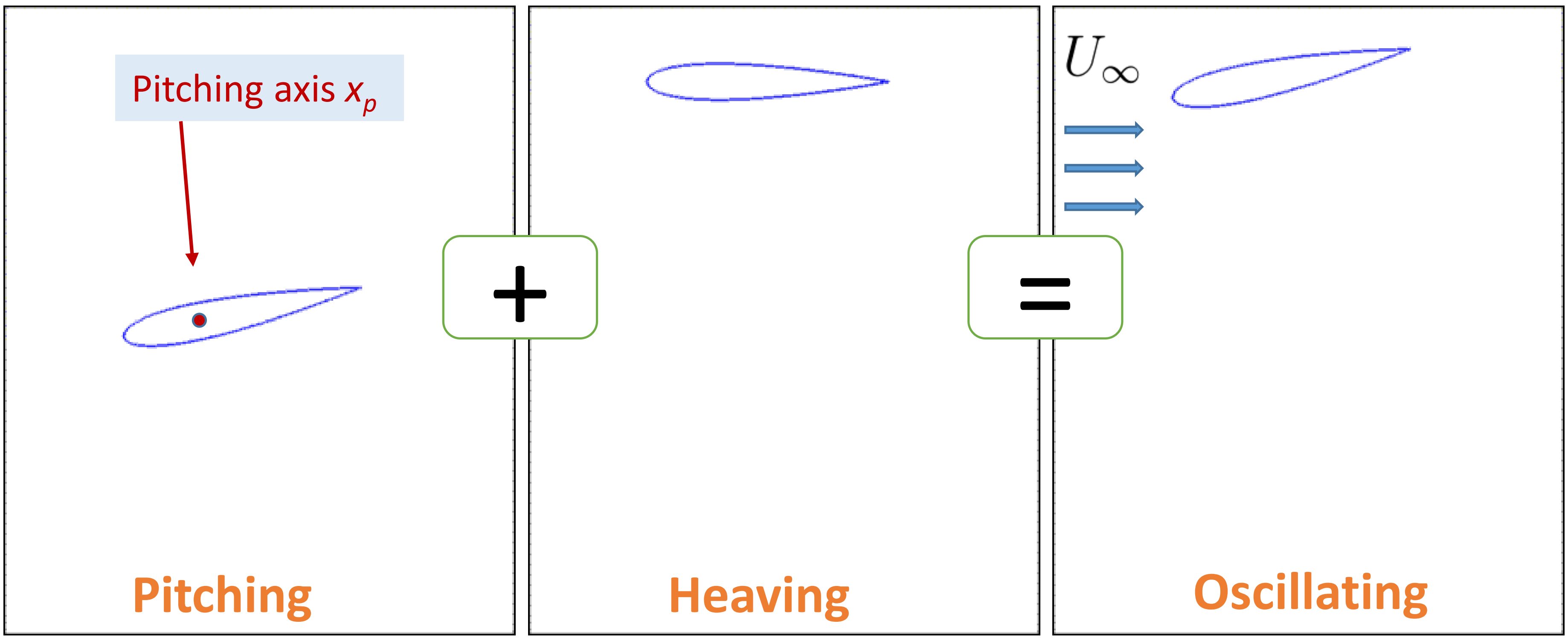


Oscillating-foil turbine

Foil motion

Frequency — Sinusoidal motions — Phase

$$\theta(t) = \theta_0 \sin(\omega t) \qquad h(t) = H_0 \sin(\omega t + \phi)$$

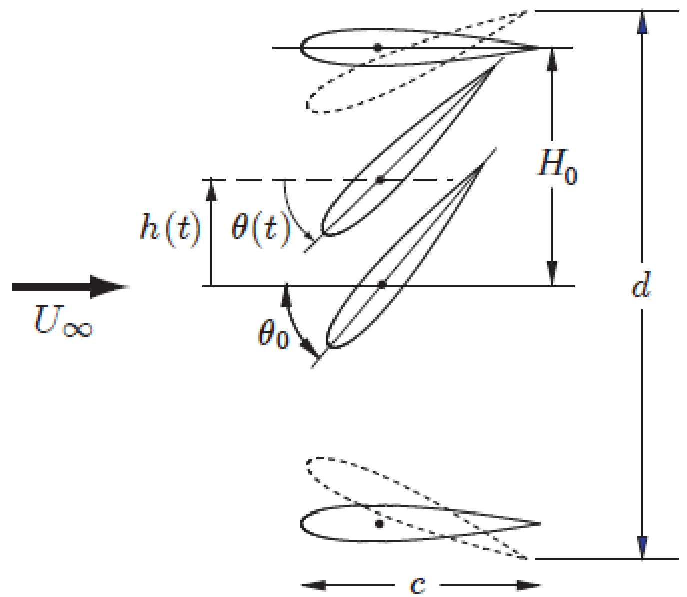


Oscillating-foil turbine

Mechanism

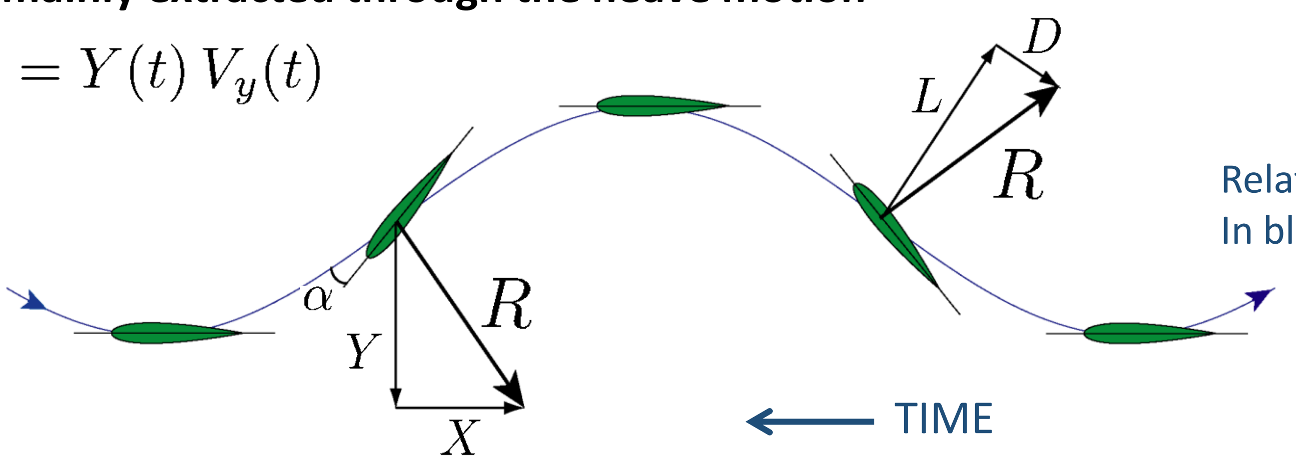
Other parameters:

- Blade profile (chord *c*)
- Heave amplitude H_0/c
- Pitch amplitude θ_0
- Reynolds number: $\mathrm{Re} = \frac{U_\infty c}{\nu}$
- Normalized frequency: $f^* = \frac{\omega}{2\pi}\frac{c}{U_\infty}$



Power mainly extracted through the heave motion

$$P_y(t) = Y(t)\,V_y(t)$$



Relative velocity
In blade's reference frame

Oscillating-foil turbine

Efficiency Mapping

Kinematically constrained foils

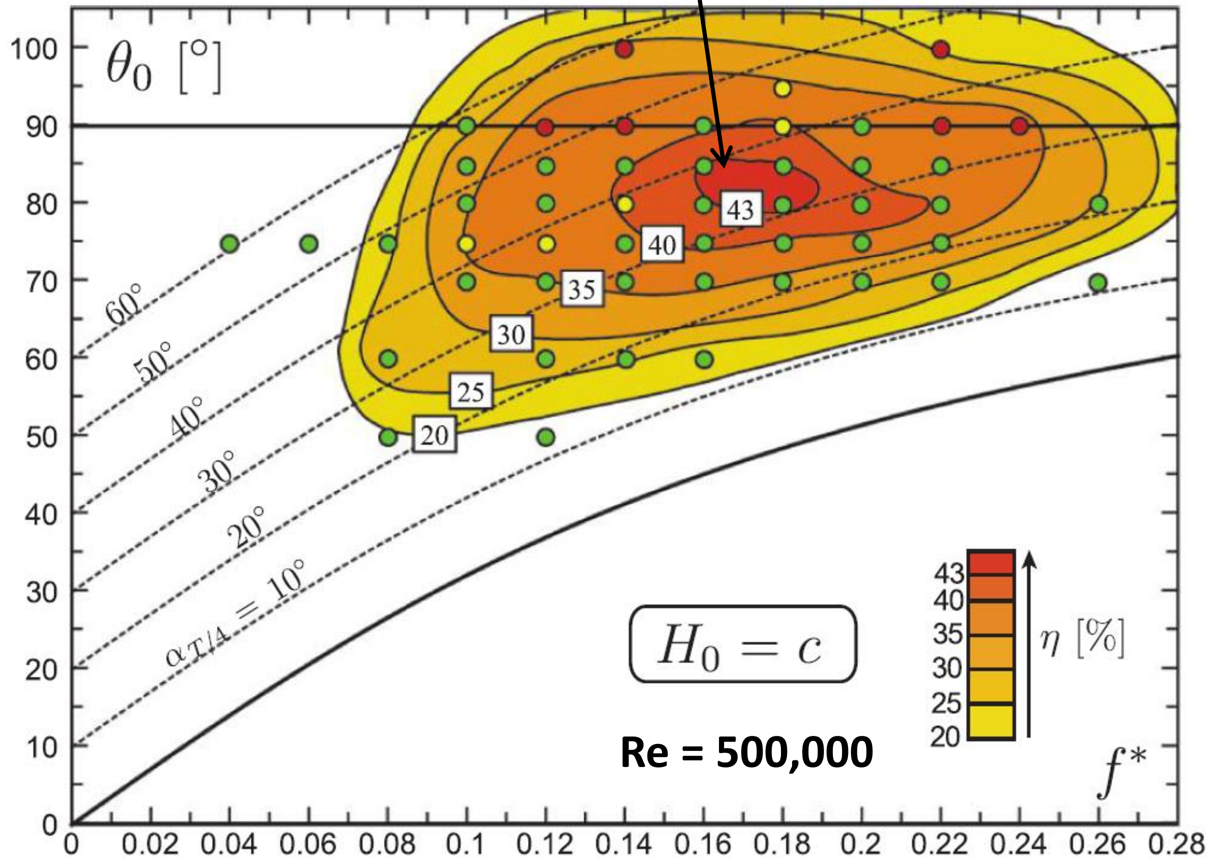
Prescribed sinusoidal motions with a phase lag of 90°
NACA 0015

Best performances at:

- Large pitching amplitudes $\Theta_0 \approx 80^o$
- and normalized frequency $f^* \approx 0.18.$

Maximum effective angle of attack $\alpha_{T/4} \approx 35^o$

$\eta_H = 43\ \%$



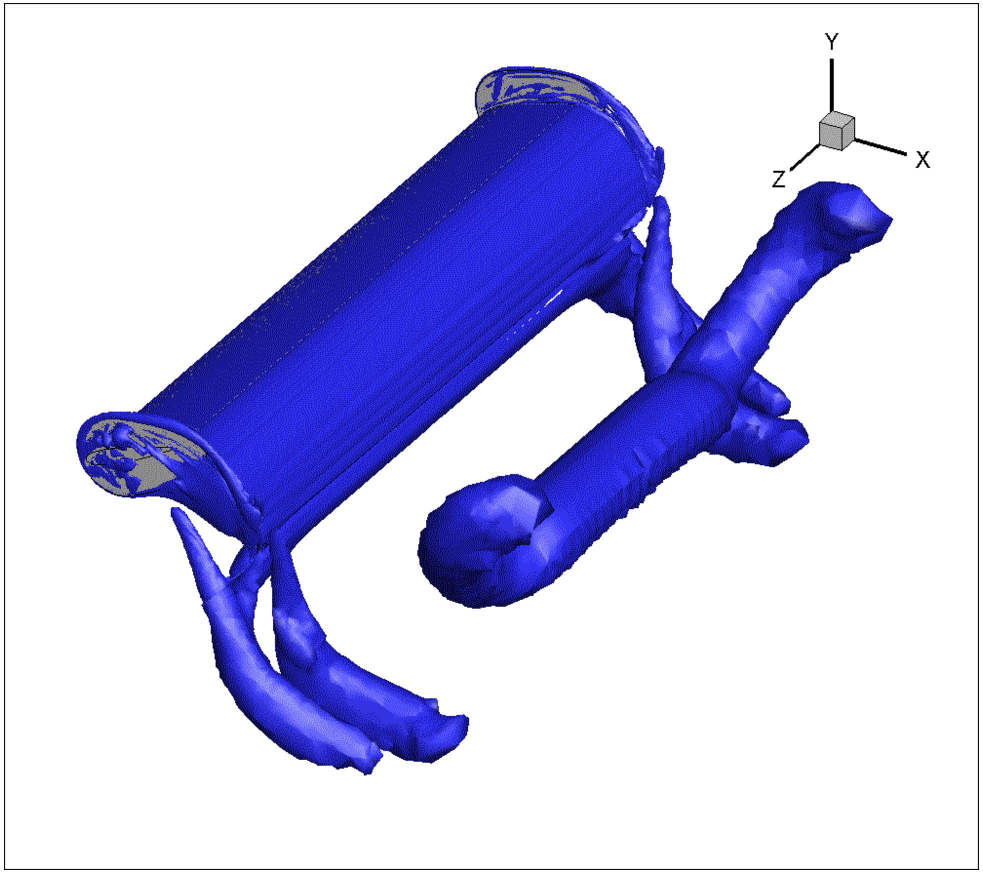
Kinsey & Dumas, AIAA J. 2008
Kinsey & Dumas, AIAA J. 2014

Oscillating-foil turbine

3D EFFECTS

Oscillating foil with end-plates (AR = 5)

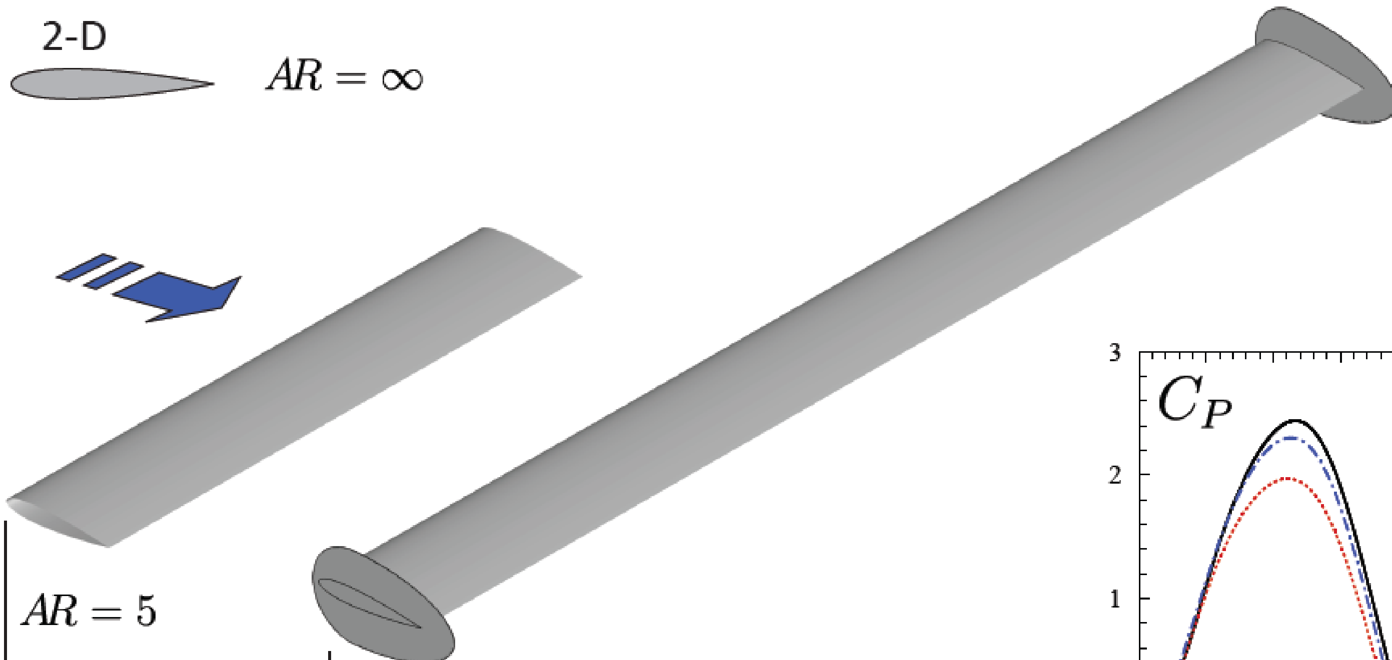
- 3D URANS simulations



Oscillating-foil turbine

3D EFFECTS

2-D



$AR = \infty$

$AR = 5$

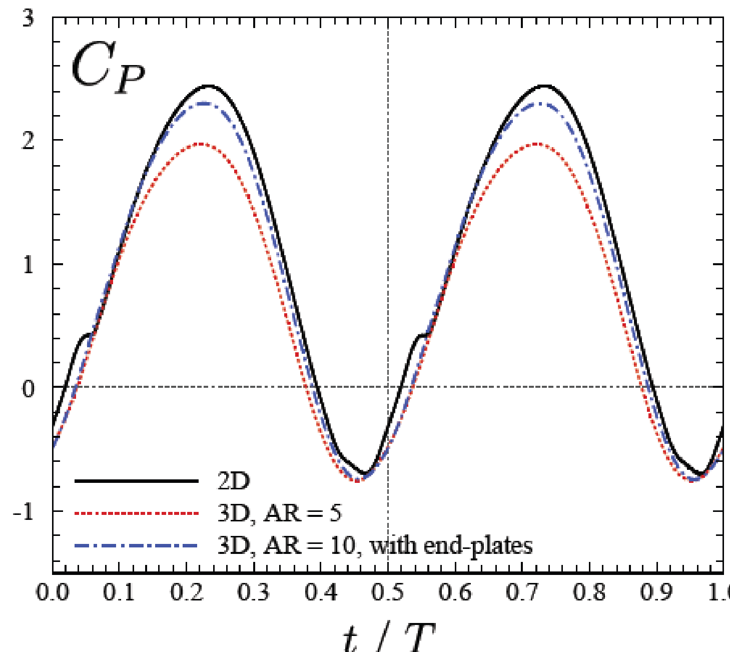
$\frac{\eta}{\eta_{2D}} \simeq 70\,\%$

$AR = 10$
with end-plates

$\frac{\eta}{\eta_{2D}} \simeq 90\,\%$

Power coefficient

$$C_P(t) = \frac{P(t)}{1/2\,\rho\,U_\infty^3\,c\,b}$$

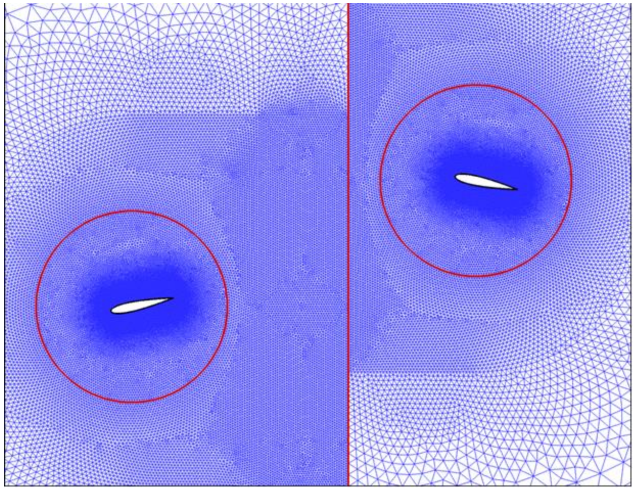


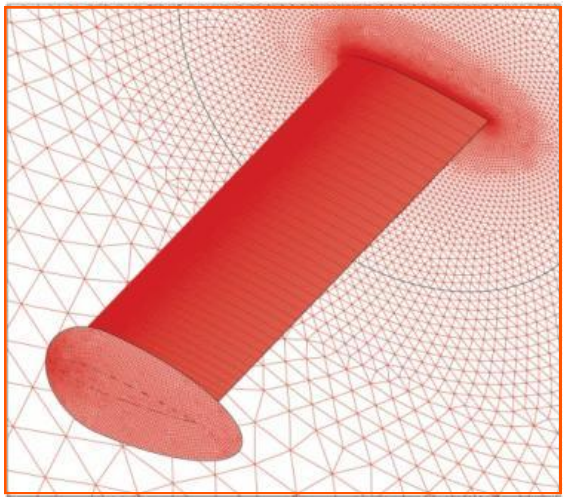
Kinsey & Dumas, JFE 2012a
Kinsey & Dumas, JFE 2012c

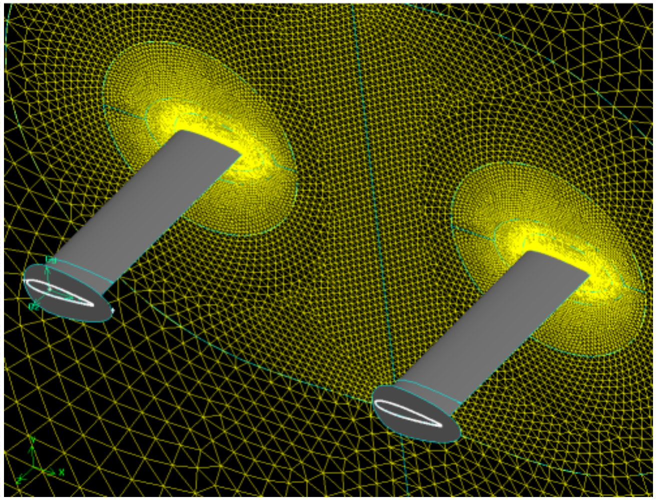
Oscillating-foil turbine

Multiple foils configurations

Oscillating Foils in Tandem





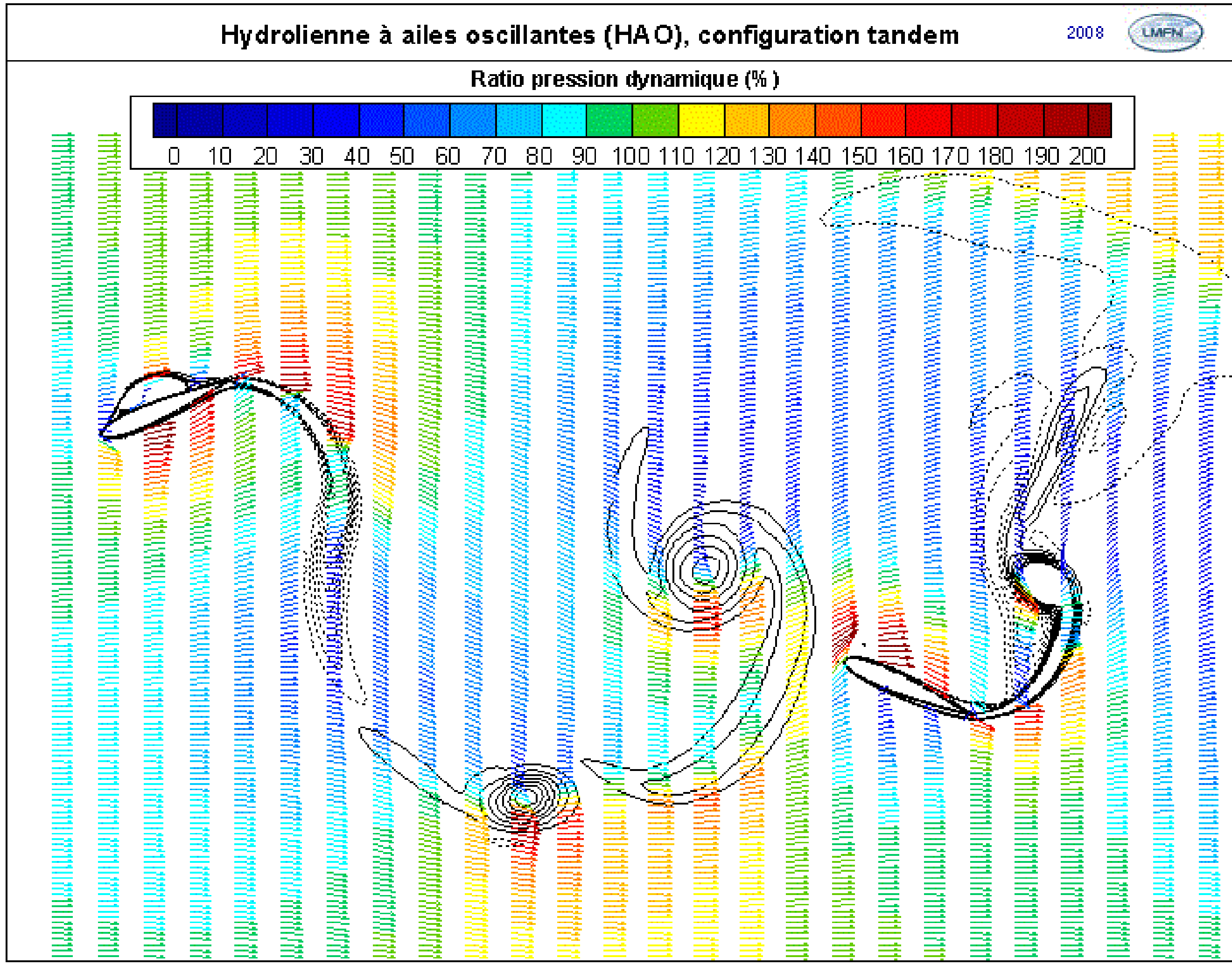


Kinsey & Dumas, JFE 2012b
Kinsey et al., Ren. Energy 2011

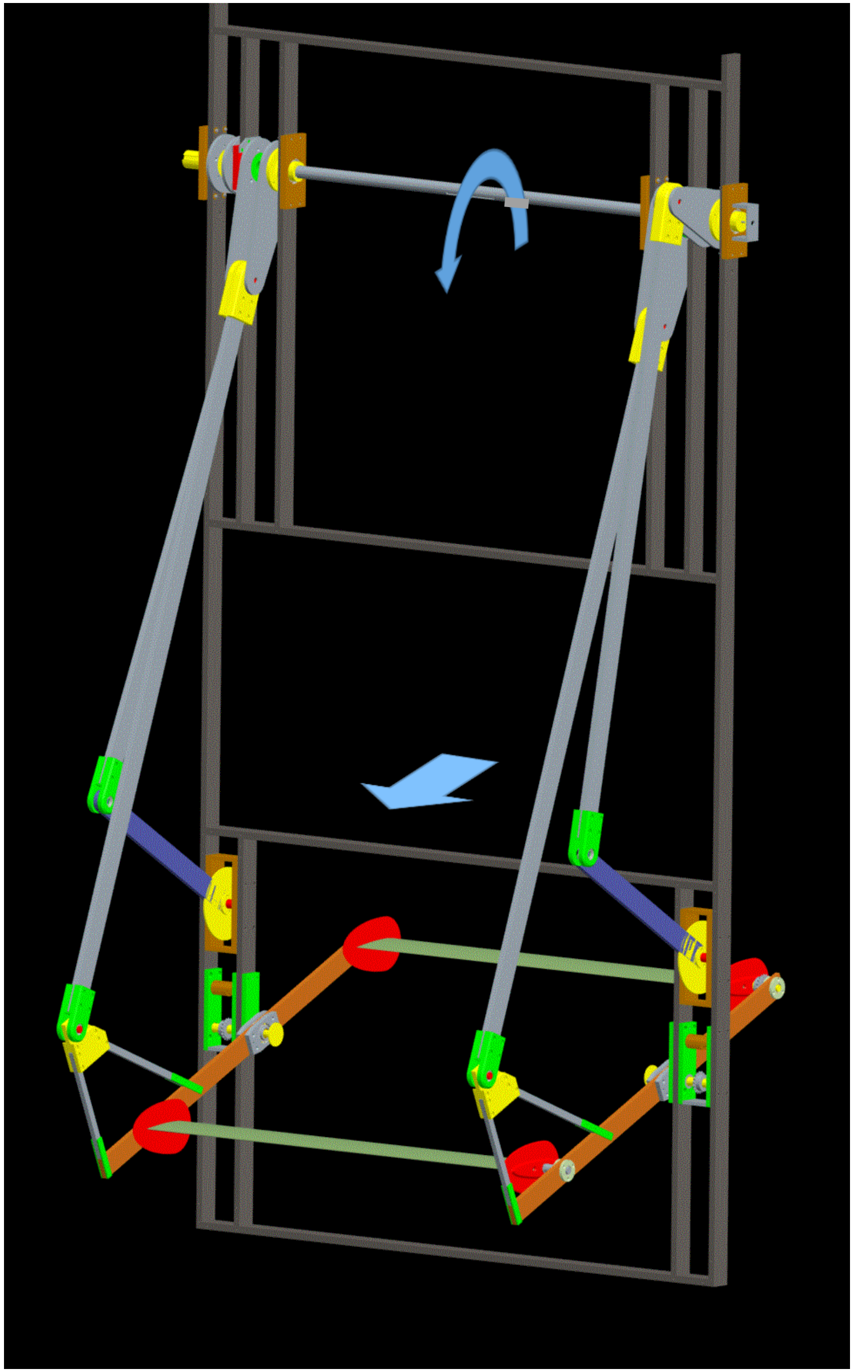
Oscillating-foil turbine

Multiple foils configurations

Oscillating Foils in Tandem



Kinsey & Dumas, JFE 2012b
Kinsey et al., Ren. Energy 2011



2kW prototype

Tandem configuration

Heaving and pitching motions **coupled to a rotating shaft** in a 1 dof embodiment.

Mechanism details

heaving:
- Duplicated four-link mechanism (crankshaft and aluminum rods)

pitching:
- Two four-link mechanism phase-shifted 180°
- 2 chains and three sprockets per hydrofoil

Oscillating-foils turbine

Experimental validation

Experimental campaign: prototype towed under a pontoon on a lake

Kinsey, Dumas et al., Renew. Energy 2011

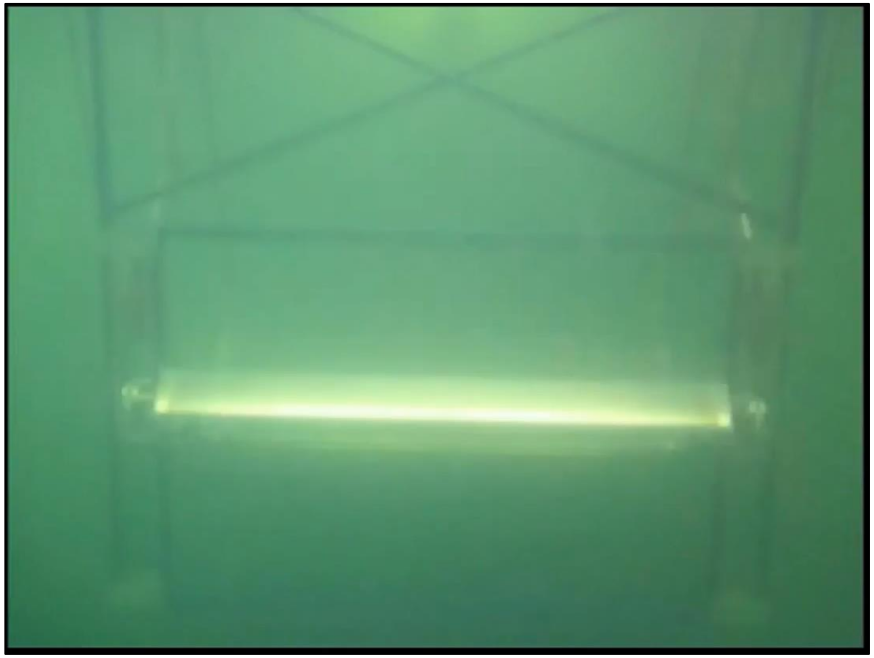
Web site:
http://hydrolienne.fsg.ulaval.ca

Oscillating-foils turbine

Experimental validation

Experimental campaign: prototype towed under a pontoon on a lake

- **Good hydrodynamic efficiency demonstrated: $\eta_H \approx 40\ \%$ (tandem)**



- **25% of the extracted power was lost before reaching the generator**

Kinsey, Dumas et al., Renew. Energy 2011

Web site:
http://hydrolienne.fsg.ulaval.ca

Oscillating-foils turbine

Improving on a good concept

Fully-constrained OFTs

- are good hydrodynamically
- but require complex mechanisms
  with imperfect efficiencies

  to impose the kinematics of both motions.

Heave	Pitch
Motion shape	Motion shape
Frequency	Frequency
Phase lag between both DOF	

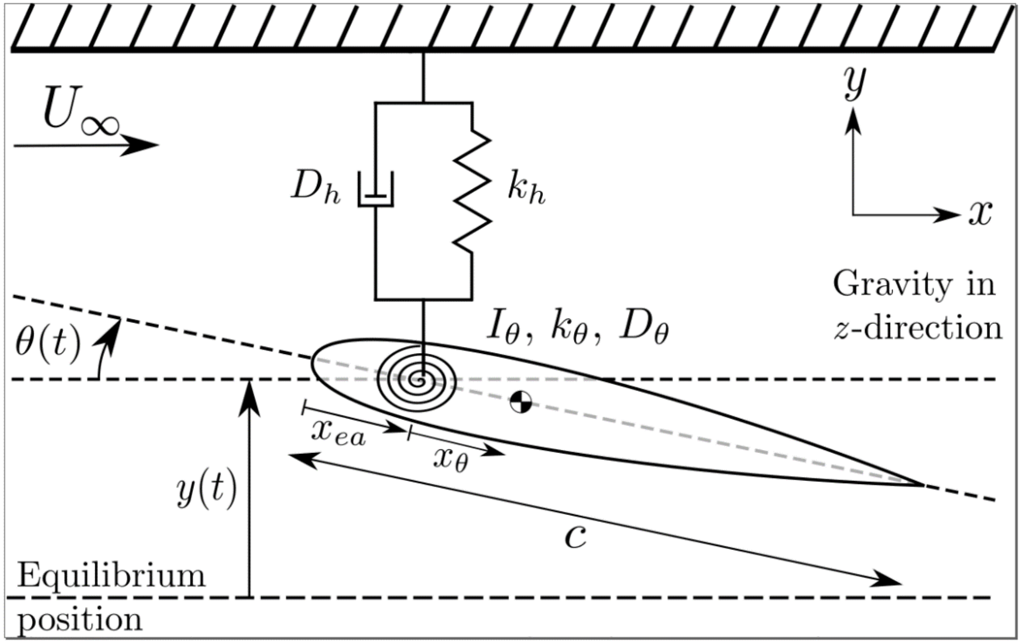
Two options:

1. Improve the mechanical design (robustness, simplicity, efficiency)
2. Free the kinematics of both motions !!!

→ ***Very promising avenue for the next generation of OFTs !***

Fully-Passive OFT

Veilleux & Dumas, JFS 2017



- Elastically-mounted foil
- Free to heave and free to pitch unconstrained !
- Self-induced and self-sustained motions
- Different types of motion can be observed
- Many parameters…

Aerodynamic forces
Inertia
Inertial coupling
Elastic supports

$$F_h = m_h\,\ddot{h} + m_\theta x_\theta \left(\ddot{\theta}\cos\theta - \dot{\theta}^2\ \sin\theta\right) + D_h\,\dot{h} + k_h\,h$$

$$M_a = I_\theta\,\ddot{\theta} + m_\theta x_\theta\,(\ddot{y}\ \cos\theta) + D_\theta\,\dot{\theta} + k_\theta\,\theta$$

Staggered implicit **FSI solver** implemented with JAVA macros in Star-CCM+

Fully-Passive OFT

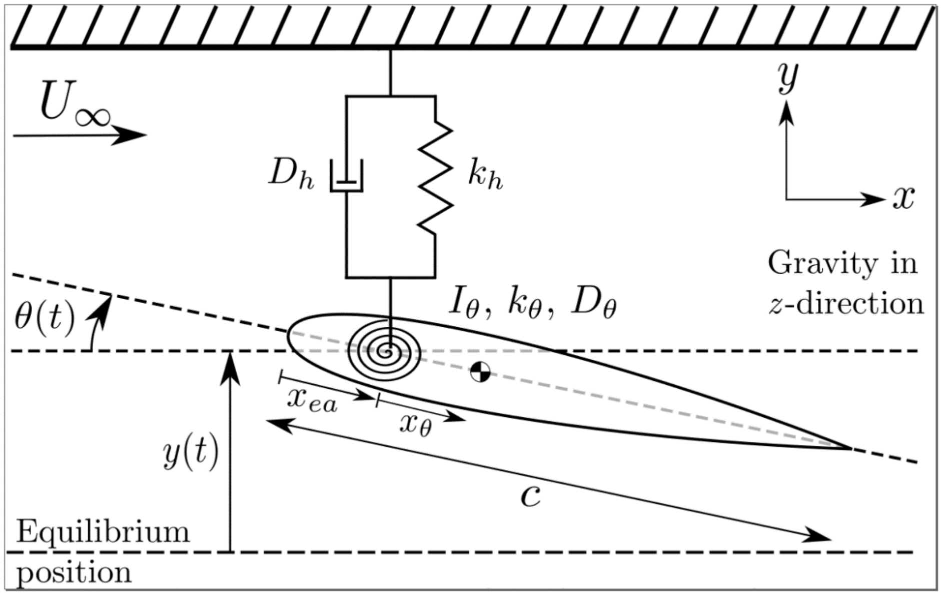
The challenge

Finding a set of parameters
(spring stiffnesses, mass, mass distribution, position of pitch axis, …)
resulting in optimal motions,

i.e., periodic and of large amplitudes,

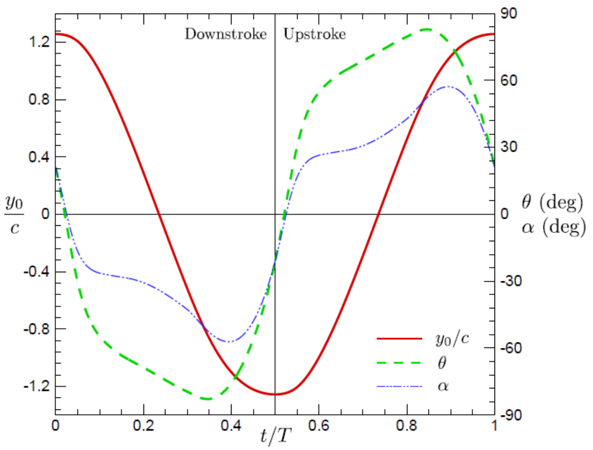
similar to the pitch and heave motions of

the high-efficiency fully-constrained OFT.



Veilleux & Dumas, JFS 2017

Boudreau, Dumas et al., JFS 2018



Veilleux's fully-passive case:

$$\eta_{H_{net}} = \frac{\bar{P}_{D\,\text{heave}}}{\frac{1}{2}\rho\, U_\infty^3\, b\, d} = 29\ \%,$$

$$\bar{C}_{P_{H_{net}}} = \frac{\bar{P}_{D\,\text{heave}}}{\frac{1}{2}\rho\, U_\infty^3\, b\, c} = 0.94,$$

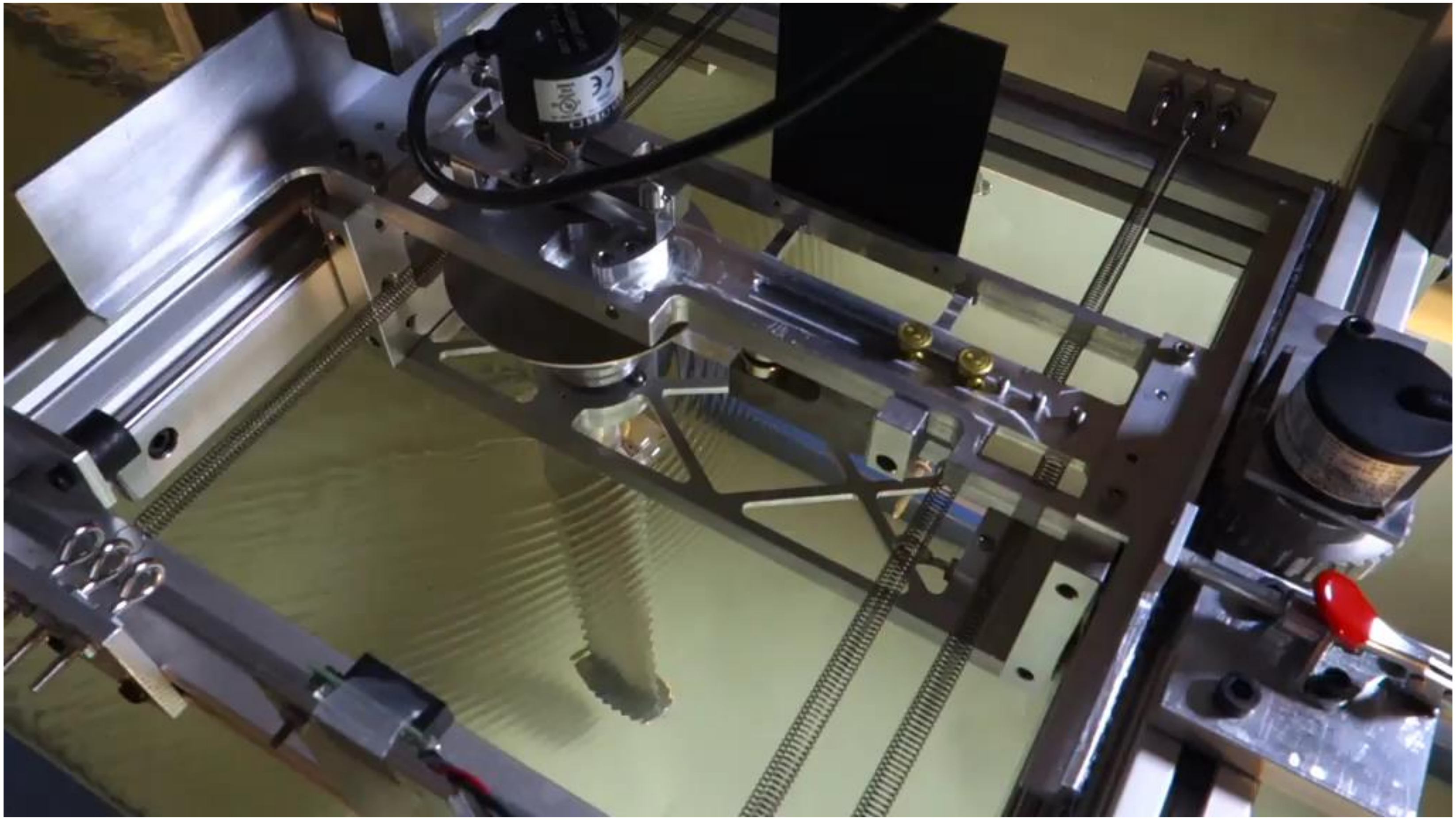
$$f^* = 0.096,$$

Fully-Passive OFT

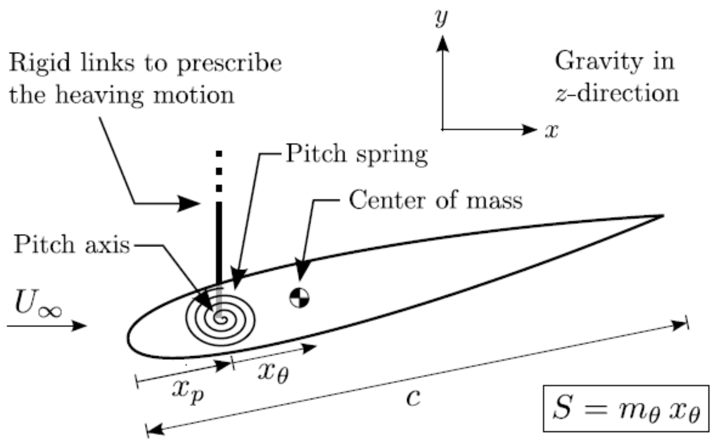
Experimental validation

- Periodic and self-induced motions
- Concept validated experimentally

Boudreau, Dumas, Rahimpour, Oshkai, JFS 2018



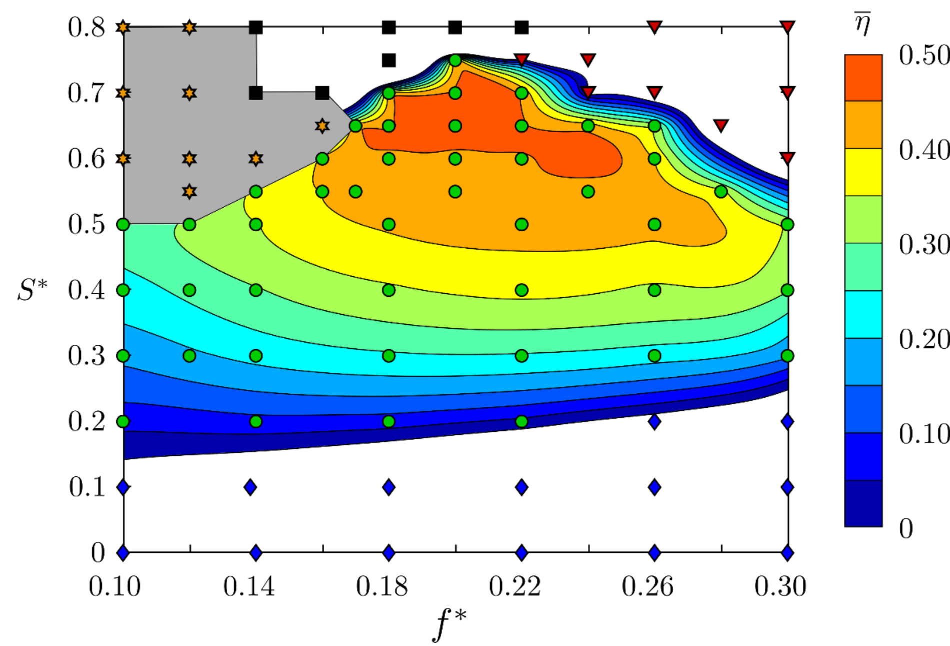
Semi-Passive Oscillating-Foil Turbine



$$h(t) = H_0 \sin(2\,\pi\, f\, t)$$

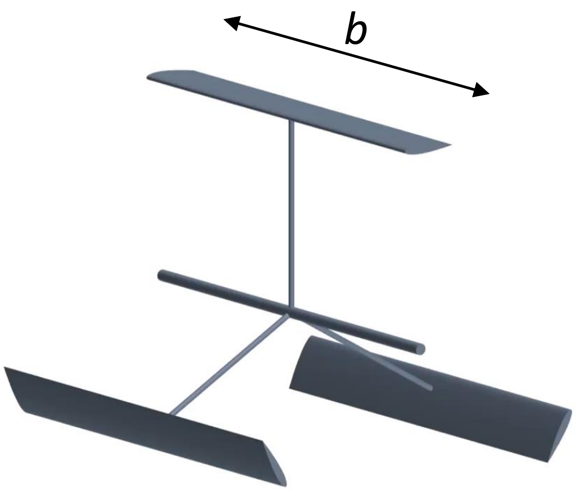
$$M = I_\theta\,\ddot{\theta} + S\,\ddot{h}\cos(\theta) + k_\theta\,\theta$$

- Sinusoidally **IMPOSED HEAVE** (with generator/controller)
- Regular and periodic **PASSIVE PITCH** resulting
- 2D efficiencies exceeding 45%
- Importance of static moment *S*



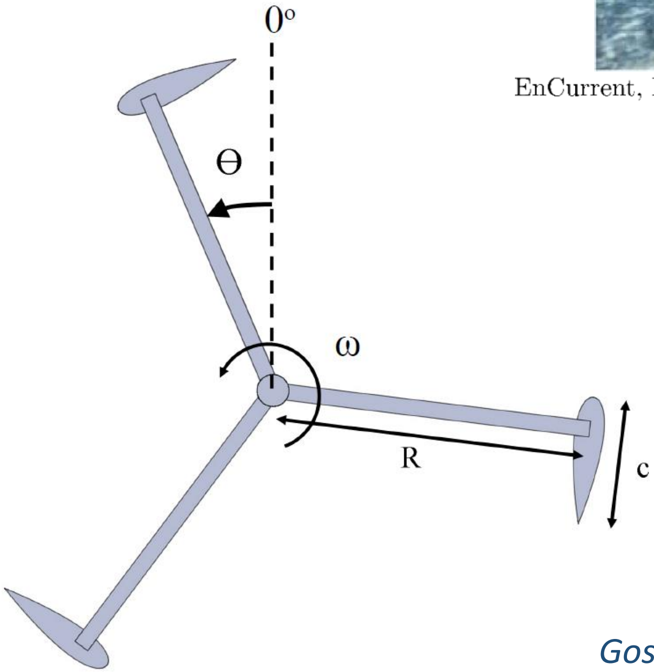
Boudreau, Gunther, Dumas, JFS 2018

Cross-Flow Turbine



$\eta \sim 40\%$

EnCurrent, New Energy Corporation (www.newenergycorp.ca)



- NACA 0015
- N
- β_{pitch}
- $\sigma = \frac{Nc}{R}$

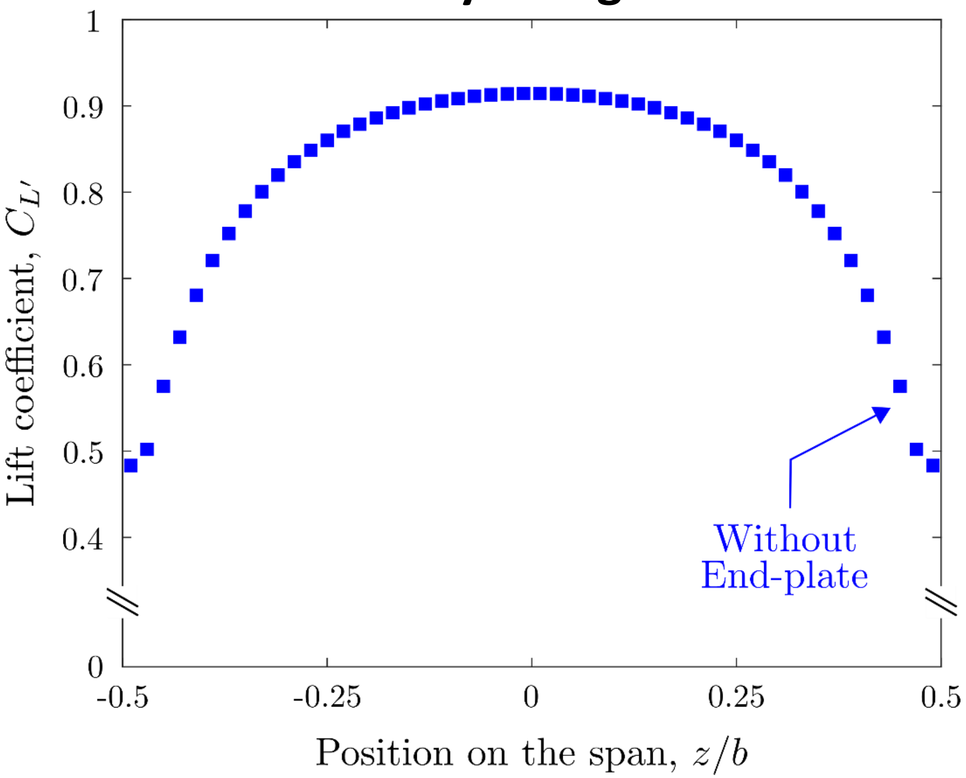
- $TSR = \frac{\omega R}{U}$
- b/D
- $Re = \frac{UD}{\nu}$

Gosselin, Dumas, Boudreau, JRSE 2016

Cross-Flow Turbine

- Tip losses

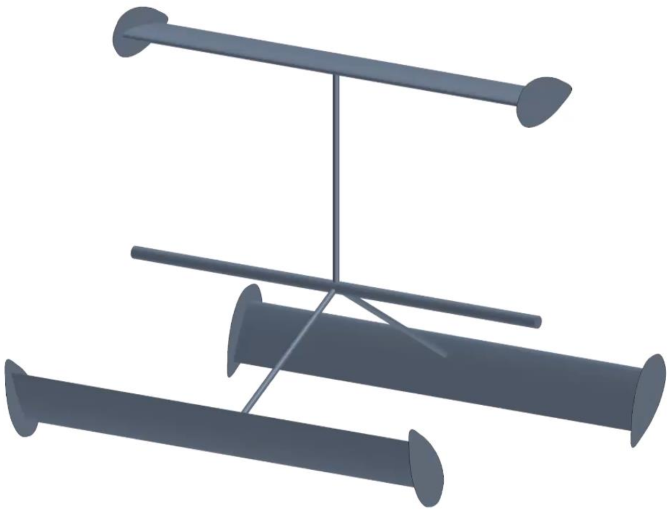
Stationary lifting blade



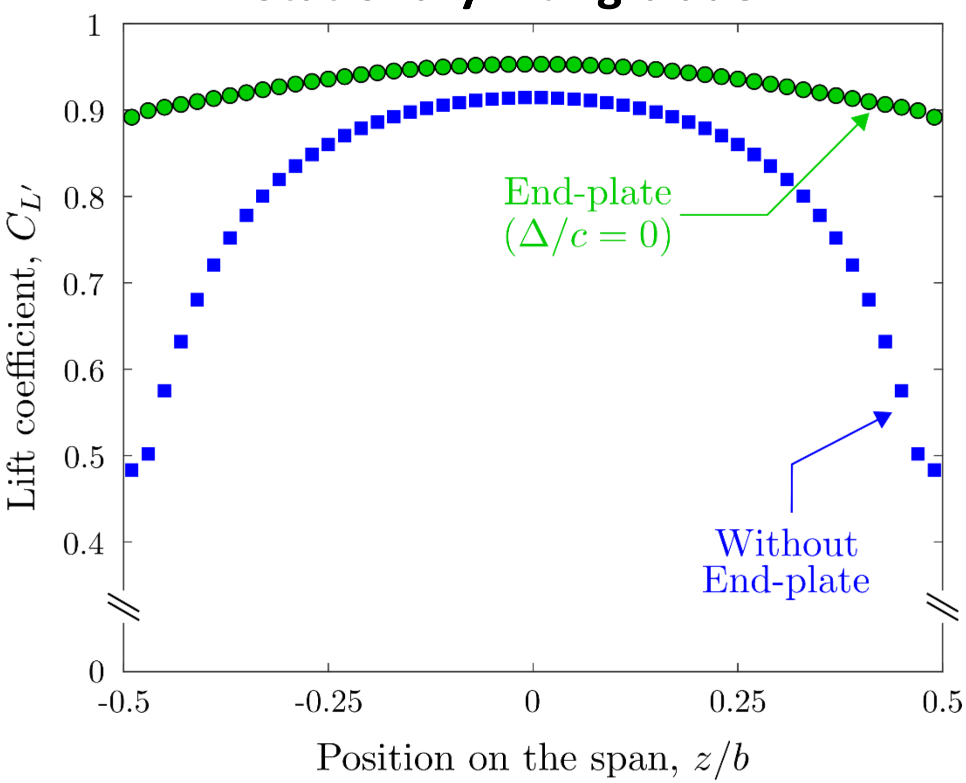
Villeneuve, Boudreau, Dumas, JWEIA 2019

Cross-Flow Turbine

- End-plates



Stationary lifting blade

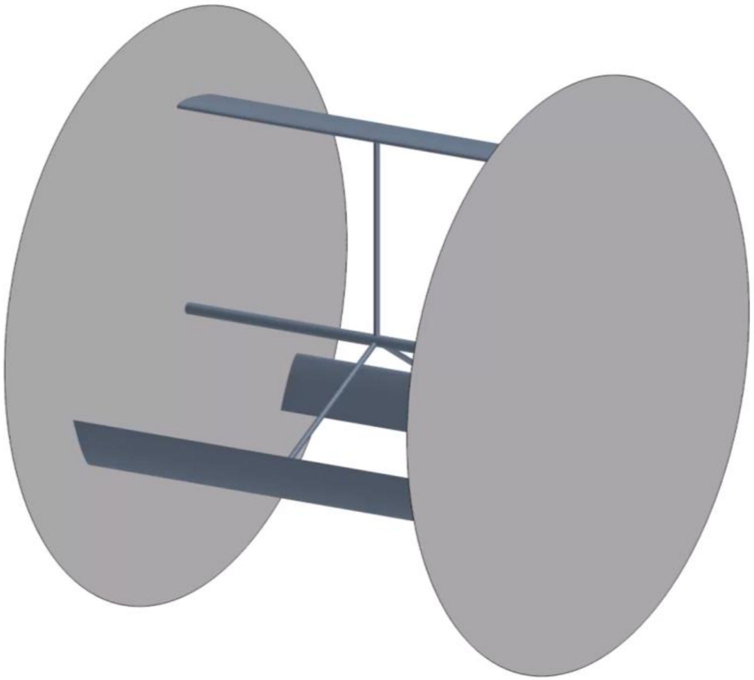


- Increase the section lift, moslty near the tips

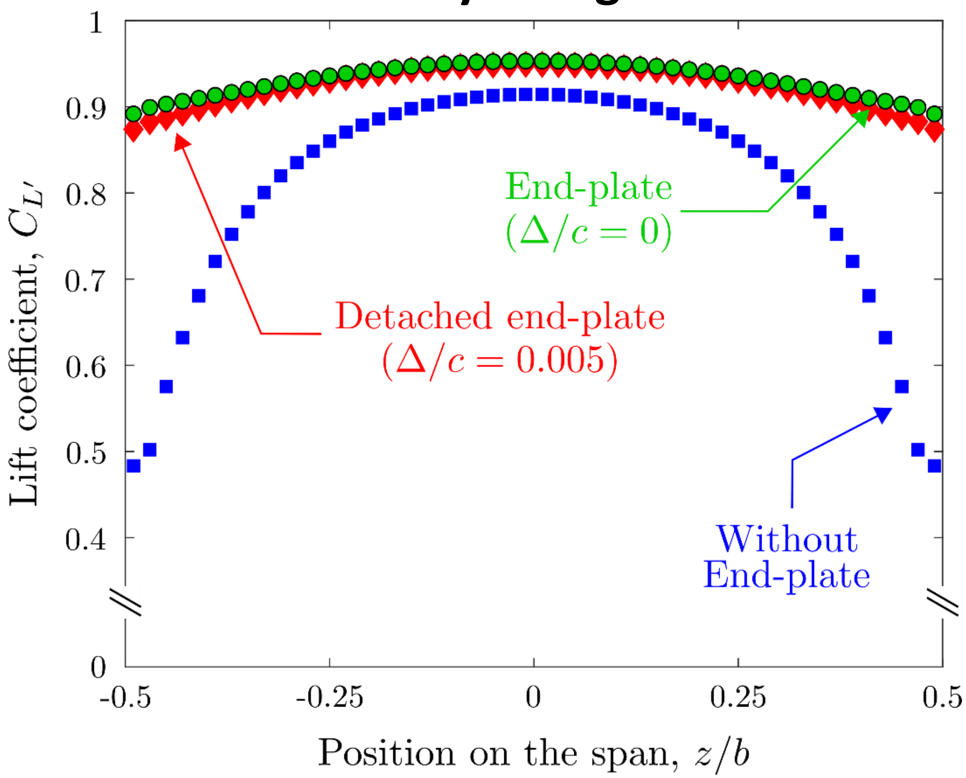
Villeneuve, Boudreau, Dumas, JWEIA 2019

Cross-Flow Turbine

- Fixed detached end-plates



Stationary lifting blade



- Increase the section lift, almost as much as the attached end-plates but with no added drag on the blades

Villeneuve, APS/DFD 2017

Cross-Flow Turbine

Semi-annular detached end-plates

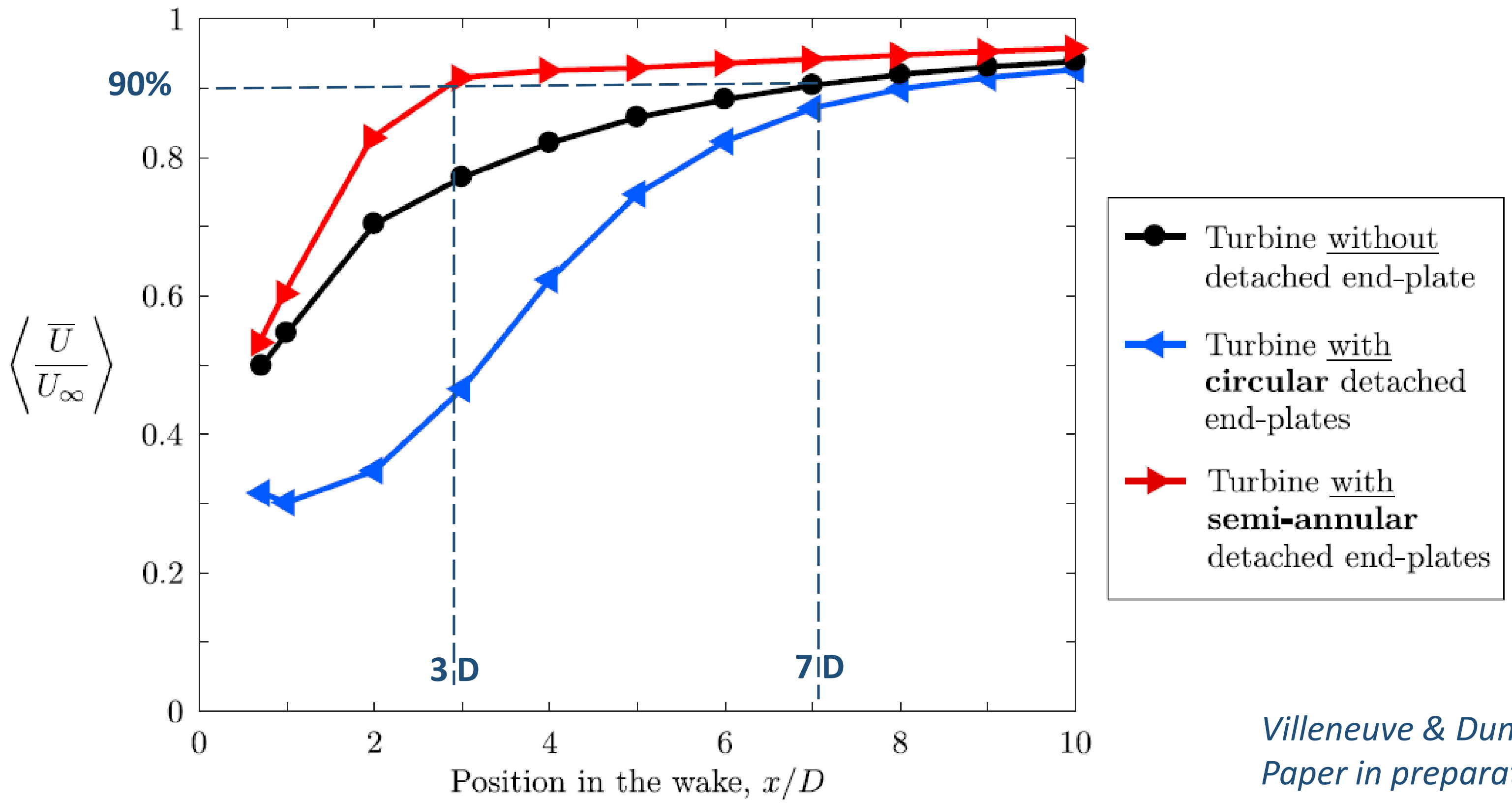
- Increase the energy extraction without penalising the good wake-recovery characteristics of the CFTs

Villeneuve, APS/DFD 2018

Cross-Flow Turbine – Wake recovery

Mean streamwise velocity recovery

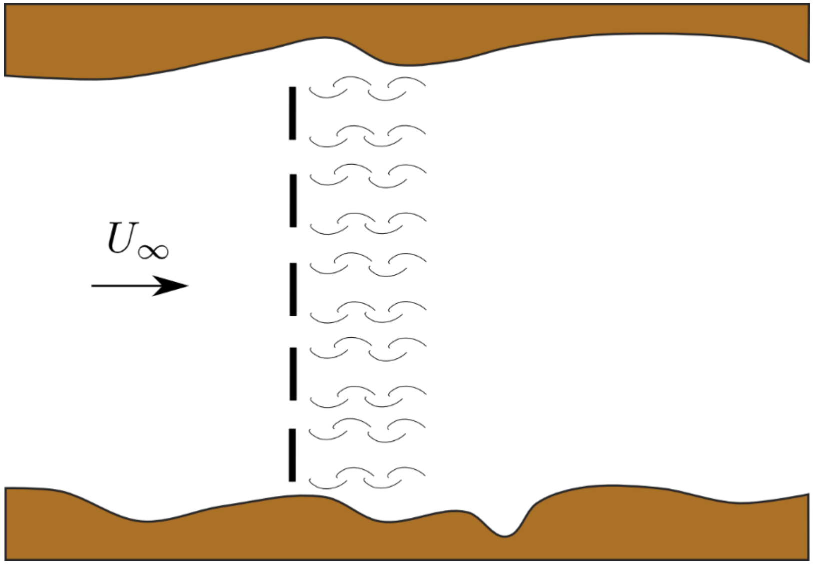
$\left\langle \frac{\overline{U}}{U_\infty} \right\rangle$: Section-averaged mean streamwise velocity



Villeneuve & Dumas, 2019
Paper in preparation…

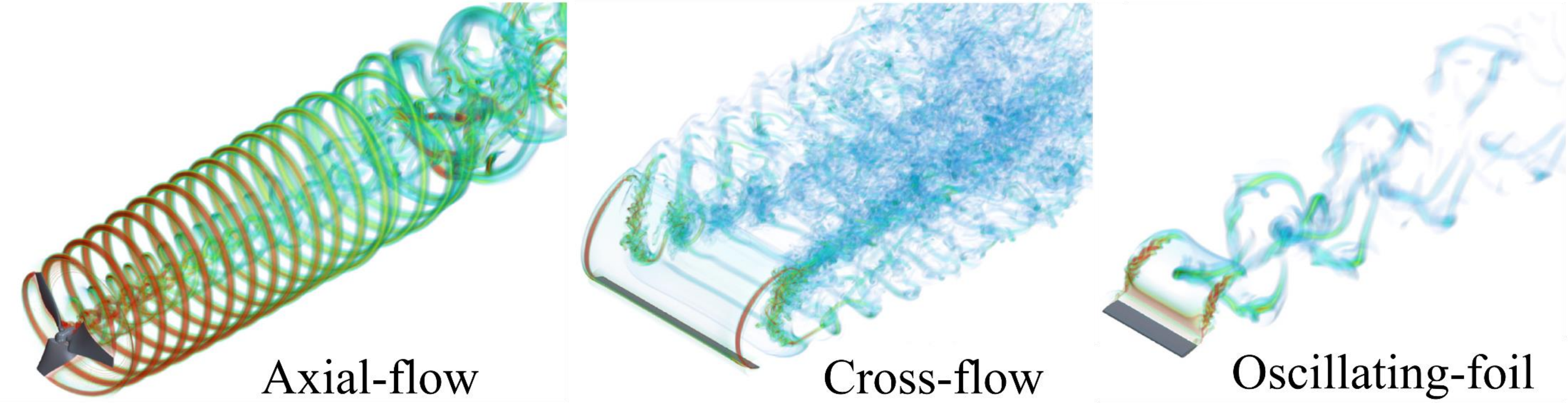
Turbine Array --- New Challenges

1. **Turbine-wake interactions**
   - Less K.E. flux available
   - More turbulent and perturbed flow conditions
2. **Blockage effects**
   - Turbine drag
   - More or less confinement of by-pass flow
   - Two scales: local and global



Wake Recovery

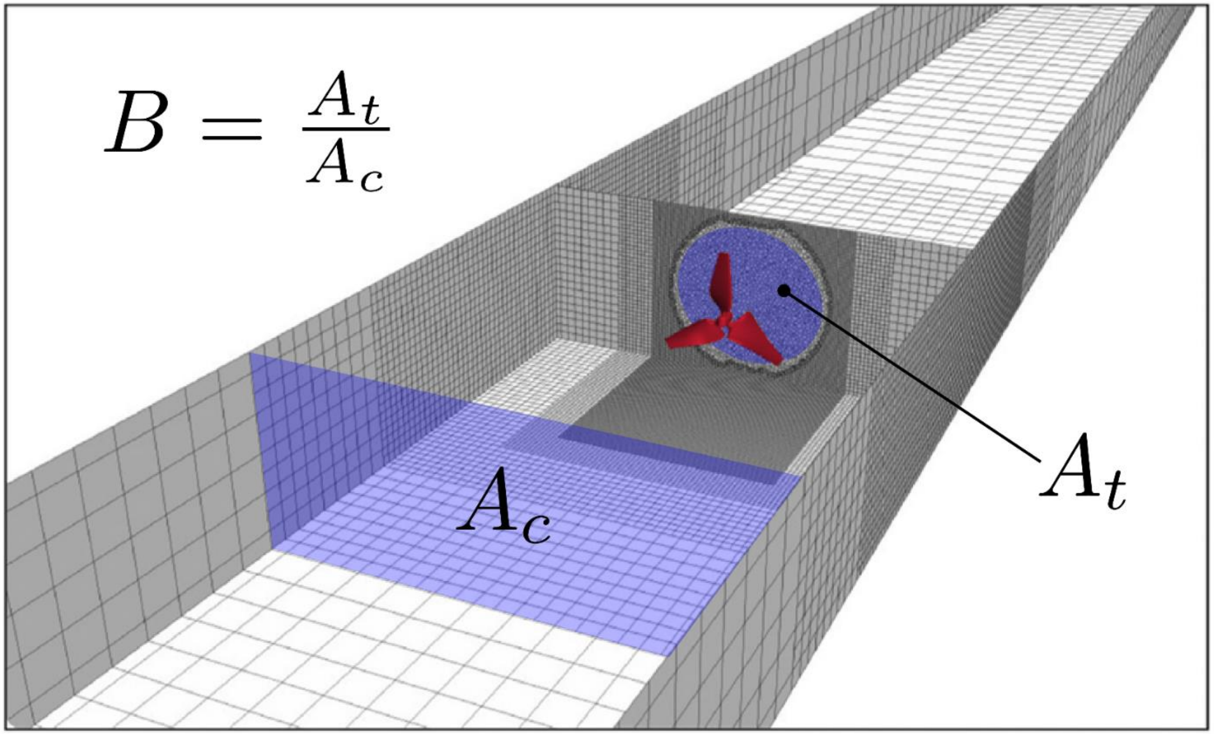
- High-fidelity simulations : DDES approach
- Vortex dynamics and wake recovery mechanisms



Boudreau & Dumas, JWEIA 2017
Boudreau & Dumas, JFE 2018

Blockage Effects

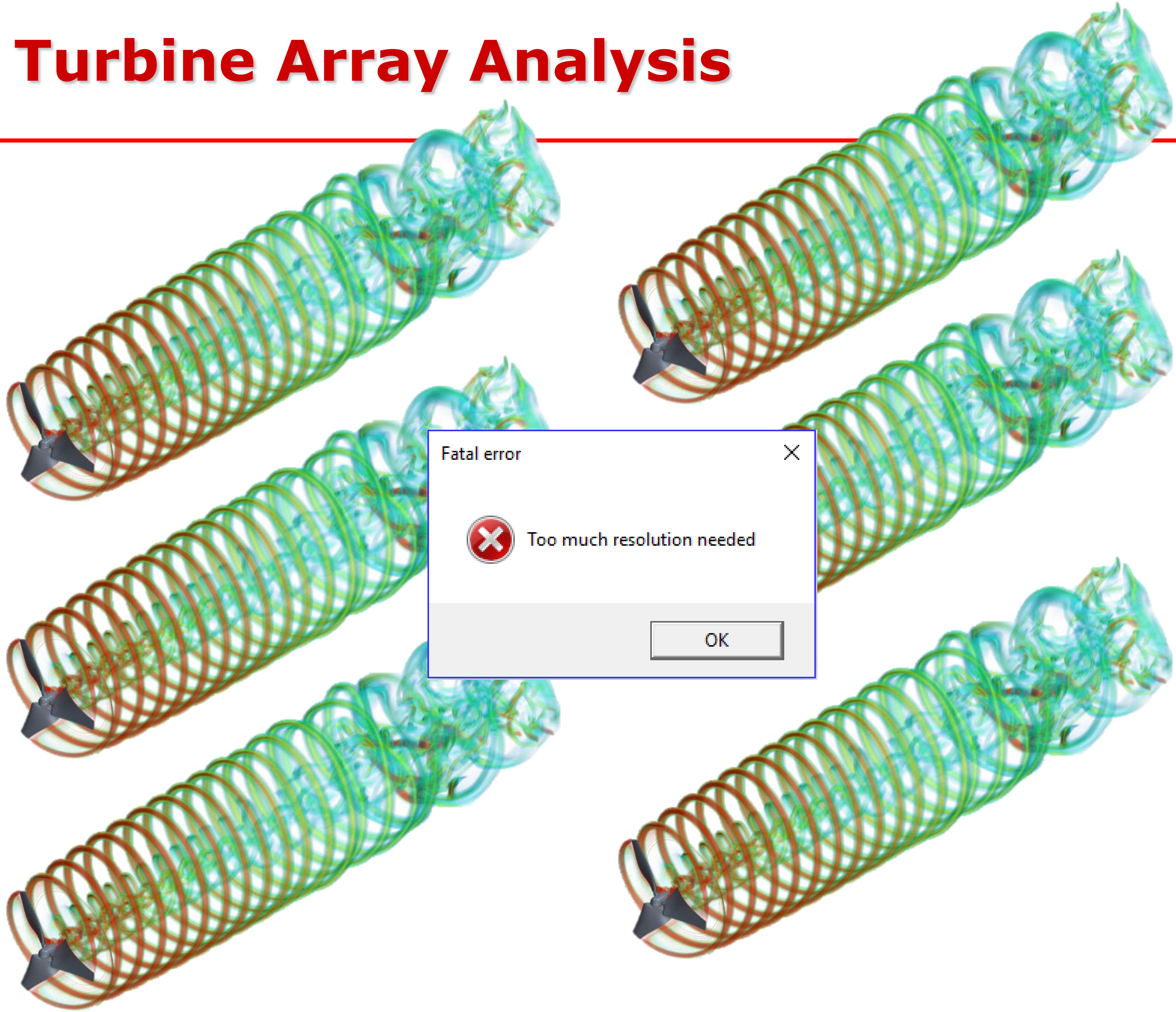
- Characteristic of marine turbine farms
- Increase turbine drag and power



$$C_D \propto B$$
$$C_P \propto B$$

Gauthier et al., JFE 2016
Kinsey & Dumas, RE 2017

Turbine Array Analysis

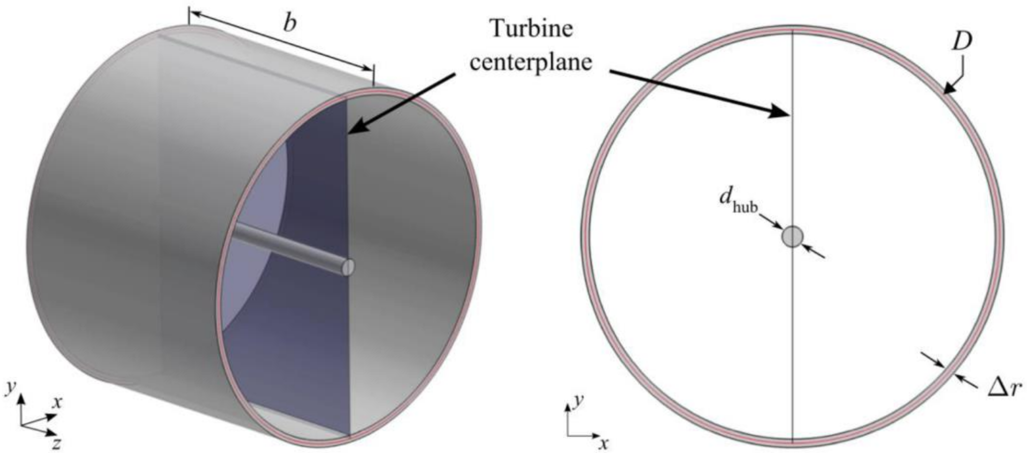


Turbine Array Modeling

Simplified, cost-effective, turbine model: EPTM

- Each technology at its BOP: EPTM-AFT; EPTM-CFT; …
- Generates the mean impact of the turbine in the flow (induces same blockage, produces realistic near-wake)
- Allows prediction of each turbine power extraction
- Reduces computational cost (steady RANS analysis of the array in its deployment site)

Full-rotor



***Effective Performance Turbine Model* (EPTM)**

Bourget et al., TCSME 2018

Effective Performance Turbine Model (EPTM)

➢ Main characteristics of proposed EPTM:

1. uses a local velocity scale V^* **("effective velocity")** and corresponding force coefficients;
2. generates **forces in all three directions** (3D), not only F_x (the thrust or drag);
3. distributes volumetric forces **non-uniformly**, and realistically, through the **actuating volume** associated to the rotor.

$$F_X = C_X^* \frac{1}{2}\rho {V^*}^2 A$$

$$F_\theta = C_\theta^* \frac{1}{2}\rho {V^*}^2 A$$

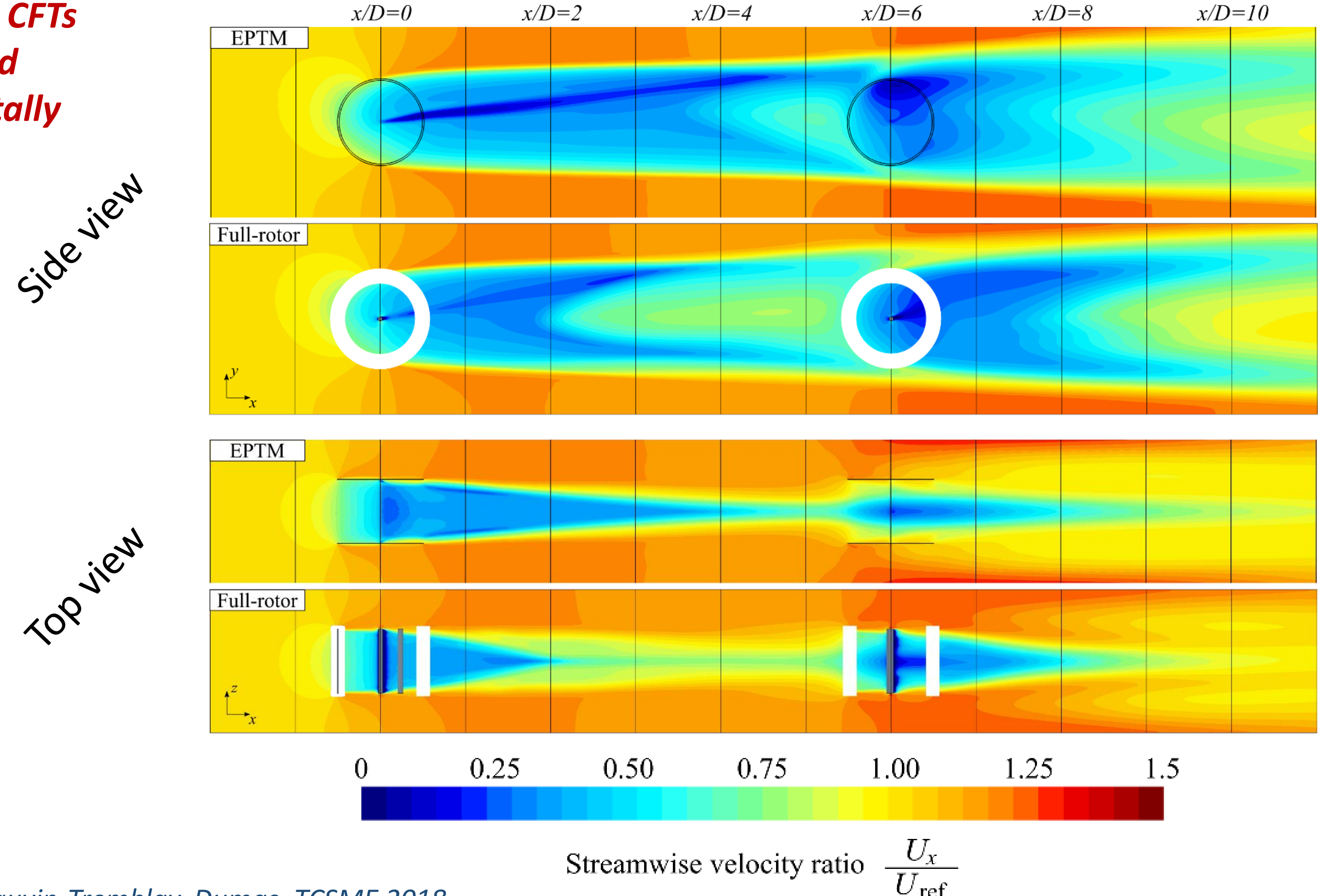
$$F_R = C_R^* \frac{1}{2}\rho {V^*}^2 A$$

$$\boldsymbol{C_P^* \equiv \frac{\overline{P}}{\frac{1}{2}\rho {V^*}^3 A}}$$

The necessary information to built the particular EPTM associated to a given turbine is a single full CFD simulation of that turbine at optimal conditions

Turbine Array Modeling

Tandem CFTs deployed horizontally



Bourget, Gauvin-Tremblay, Dumas, TCSME 2018

Conclusion

- **Progress has been quite encouraging**
- **CFD has been a vital tool to develop and improve turbine technologies**
- **Prototype demonstration is always needed**

FUTURE WORK

- **Design and testing of a semi-passive OFT turbine (proof of concept)**
- **Continue CFD optimization of turbine technologies**
- **Produce guidelines for optimal turbine array configurations**
- **Continue validation and improvement of the EPTM approach**

Most needed:

Detailed experimental data of turbine arrays (performances and wakes) operating at realistic Reynolds number

Thank you for your attention.
Questions?