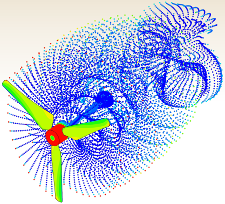

Développements et applications autour du logiciel DOROTHY

Journée Scientifique HPC du CRIANN

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21/10/2021

Laboratoire Ondes et Milieux Complexes (LOMC)
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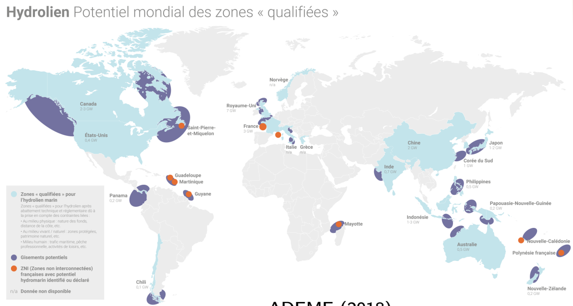
Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER)
Boulogne-sur-Mer

Outline

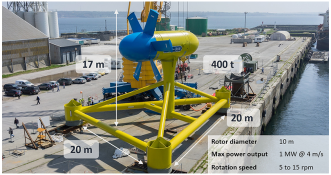
Outline

Tidal energy



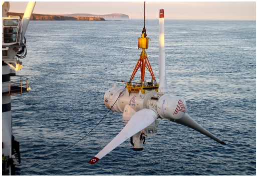
ADEME (2018)

- High potential areas.
- Few pilot projects.
- Numerical simulation necessary for predictive assessment and optimization.



Sabella

Hydroquest



Atlantis

Tidal turbines

(a) General Description

Description	IFREMER-LOMC
Blade profile	NACA 63418
Rotor radius R	350 mm
Hub radius	46 mm
hub length	720 mm
Blade angle	0°
TSR range	$[0-10]$
Direction of rotation	anti-clockwise
Reynolds number Re_∞	$[1.4-4.2] \cdot 10^5$

(b) 1/20 scaled experimental model

$$\mathrm{TSR} = \frac{\Phi_x R}{U_\infty} \quad \Big| \quad C_P = \frac{\mathcal{P}}{\mathcal{P}_\infty} = \frac{\mathcal{M}_x \Phi_x}{\frac{1}{2}\rho\pi R^2 U_\infty^3} \quad \Big| \quad C_T = \frac{\mathcal{F}_x}{\frac{1}{2}\rho\pi R^2 U_\infty^2}$$

- Φ_x : rotation speed ;
- R : radius ;
- U_∞ : upstream flow speed ;
- $\mathcal{P}$: power ;
- $\mathcal{M}_x$: axial moment ;
- $\mathcal{F}_x$: axial force.

Experimental results : importance of ambient turbulence

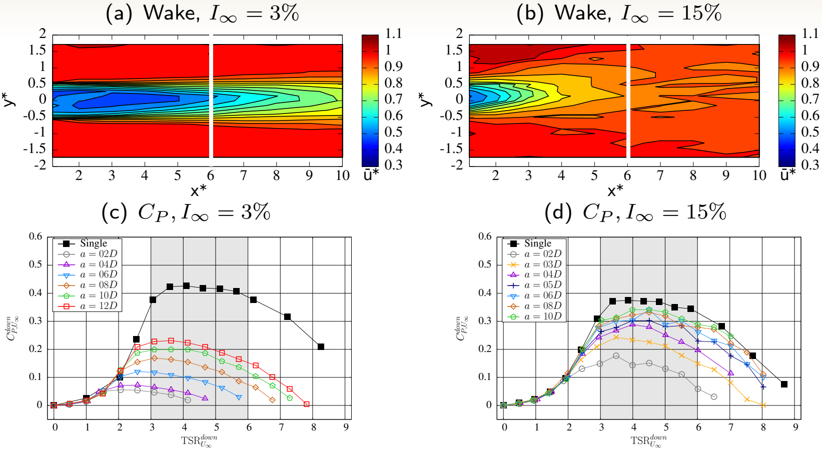


Figure – Axial velocity map (top) with $U_\infty = 0.8\,\mathrm{m}\cdot\mathrm{s}^{-1}$ and $\mathrm{TSR} = 3.67$, C_P graph (bottom) with $U_\infty = 0.8\,\mathrm{m}\cdot\mathrm{s}^{-1}$ and $\mathrm{TSR}^{up} = 4$.

Paul Mycek, Benoît Gaurier, Grégory Germain, Grégory Pinon, and Elie Rivoalen.
Experimental study of the turbulence intensity effects on marine current turbines behaviour. part II : Two interacting turbines.
Renewable Energy, 68(0) :876 – 892, 2014.

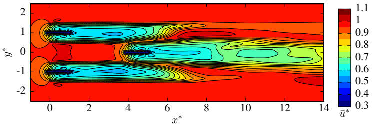
Tidal turbine simulation with DOROTHY

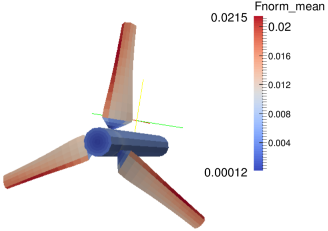
DOROTHY simulation code

- Developed at LOMC/IFREMER for the last 15 years.
- Run remotely on regional calculator CRIANN.
- Interacting tidal turbines with possibility of ambient turbulence.
- Results : performance output and wake configuration of one or multiple turbines.

Current performance

- Satisfying wake results.
- Turbine blade representation and power results require further developments.





Outline

General framework

Vortex Particle Method

- Lagrangian method ;
- Only solid obstacles represented by a surface mesh.

Governing Equations

Navier-Stokes Equations :

- Incompressible fluid,
- Velovity-vorticity formulation $(\boldsymbol{u}, \boldsymbol{\omega})$.

$$\begin{cases} \boldsymbol{\nabla} \cdot \boldsymbol{u} = 0 \\ \dfrac{\mathrm{D}\boldsymbol{\omega}}{\mathrm{D}t} = \underbrace{(\boldsymbol{\omega} \cdot \boldsymbol{\nabla})\boldsymbol{u}}_{\text{Stretching}} + \underbrace{\nu\, \boldsymbol{\nabla}^2 \boldsymbol{\omega}}_{\text{Diffusion}} \end{cases}$$

with $\dfrac{\mathrm{D}\boldsymbol{\omega}}{\mathrm{D}t} = \dfrac{\partial \boldsymbol{\omega}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{\omega}$

Fluid particles

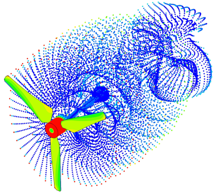
Defined by :

- Position $\boldsymbol{X}$;
- Vorticity ("weight") $\boldsymbol{\Omega}$.

G. Cottet and P. Koumoutsakos.
Vortex methods : theory and practice.
Cambridge University Press, 2000.

A. Leonard.
Vortex methods for flow simulation.
Journal of Computational Physics, 37(3) :289–335, 1980.

C. Rehbach.
Calcul numérique d'écoulements tridimensionnels instationnaires avec nappes tourbillonaires.
La Recherche Aérospatiale, 5 :289–298, 1977.



Velocity field

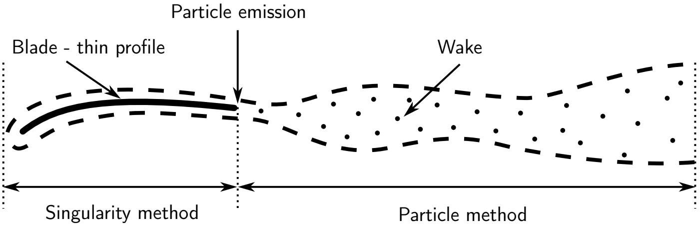
Helmholtz Decomposition

$$\boldsymbol{u} = \boldsymbol{\nabla} \times \boldsymbol{\psi} + \boldsymbol{\nabla}\phi + \boldsymbol{u}^{\infty}$$
$$= \underbrace{\boldsymbol{u}^{\psi} + \boldsymbol{u}^{\phi}}_{\text{Integral methods}} + \boldsymbol{u}^{\infty}$$

$$\boldsymbol{\nabla}^2 \boldsymbol{\psi} = -\boldsymbol{\omega}$$
$$\boldsymbol{\nabla}^2 \phi = 0$$

Velocity components

- $\boldsymbol{u}^{\psi}$: Rotational component
  $\Rightarrow$ Influence of the wake,
- $\boldsymbol{u}^{\phi}$: Potential component
  $\Rightarrow$ Influence of the turbines,
- $\boldsymbol{u}^{\infty}$: Upstream incoming velocity.



Computation of loads

Joukowski law

Pressure force linked to the vorticity attached to each mesh face :

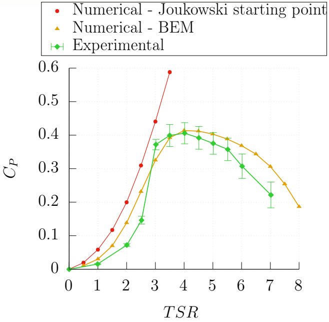
$$\mathscr{F} = \int_{\mathscr{S}} \rho \, \frac{\partial \mu}{\partial t} \, ds + \int_{\mathscr{S}} \rho \, \boldsymbol{u} \times (\boldsymbol{n} \times \boldsymbol{\nabla} \mu) \, ds$$

Blade Element Momentum Theory

Computation of loads by blade sections based on tabulated values (polar curves).

Three functioning modes

- Kutta condition → particle emission,
- BEM → computation of loads,
- Lifting line model → particle emission + computation of loads.



G. Ingram.
Wind turbine analysis using the blade element momentum method.
Technical report, School of Ingineering, Durham University, Durham, UK, October 2011.

P. Mycek.
Étude numérique et expérimentale du comportement d'hydroliennes.
PhD thesis, Université du Havre, 2013.

"Simpler" alternative : Lifting Line theory

Bound Vortex

$$\Gamma_B(r,t) = \frac{1}{2} c V_{rel} C_L$$

- Relative velocity :

$$V_{rel} = (U_x, U_\theta - \Omega r)$$

- C_L : Lift coefficient

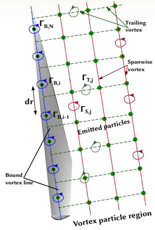
$$C_L = C_L(\alpha, Re)$$

- Trailing and spanwise vorticity :

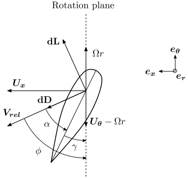
$$\Gamma_T\left(r - \frac{\mathrm{d}r}{2}, t\right) = \frac{\partial \Gamma_B(r,t)}{\partial r} dr$$

$$\Gamma_S(r,t) = \frac{\partial \Gamma_B(r,t)}{\partial t} dt$$

Jonathan Murray and Matthew Barone. (2011). "The Development of CACTUS, a Wind and Marine Turbine Performance Simulation Code" In : *49th AIAA.*

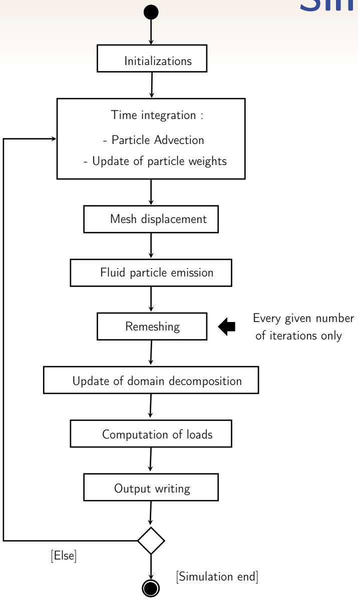


Blade vortex lattice system.

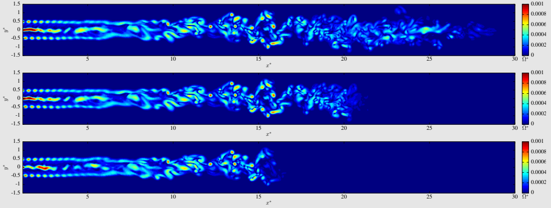


Cross-sectional blade element.

Simulation process



Artificial wake dissipation



Other optimisations

- Treecode domain decomposition : K-means clustering.
- Additional refactoring : output writing, reorganisation of loops...
- $\sim$ 18 hours $\rightarrow$ $\sim$ 5 hours for 60 sec. single turbine.

Outline

Outline

Integration of SEMs

Velocity decomposition

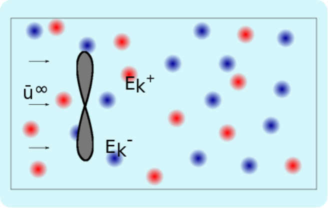
$$\boldsymbol{u} = \boldsymbol{u}^{\psi} + \boldsymbol{u}^{\phi} + \boldsymbol{u}_{\infty}$$

$\boldsymbol{u}_{\infty}$ is separated into :

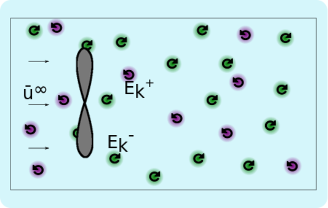
$$\boldsymbol{u}_{\infty} = \underbrace{\overline{\boldsymbol{u}_{\infty}}}_{\text{average velocity}} + \underbrace{\tilde{\boldsymbol{u}}}_{\text{fluctuating velocity}}$$

Integration into the Vortex method

- Sub-layer of turbulent structures ;
- Turbulent structures $\Rightarrow$ Turbines
  Turbines $\not\Rightarrow$ Turbulent structures ;
- Can be pictured as a "conveyer belt".



SEM (Jarrin) : sources/sinks



DFSEM (Poletto) : "eddies"

N. Jarrin.
Synthetic Inflow boundary conditions for the numerical simulation of turbulence.
PhD thesis, University of Manchester, 2008.

R. Poletto.
Divergence free develoment of the Synthetic Eddy Method in order to improve synthetic turbulence for embedded LES simulations.
PhD thesis, University of Manchester, 2014.

SEM parameters

Turbulent structures

- Position $\boldsymbol{x}$;
- Size $\boldsymbol{\lambda}$;
- Intensity $\boldsymbol{c}$.

Random parameters

- Position of the structures $\boldsymbol{x}$;
- "Sign" of the structures.

Turbulence intensity

$$I_\infty = 100\sqrt{\frac{\frac{1}{3}\left[\sigma^2(u_\infty)+\sigma^2(v_\infty)+\sigma^2(w_\infty)\right]}{\bar{u}_\infty^2+\bar{v}_\infty^2+\bar{w}_\infty^2}} = 100\sqrt{\frac{\frac{1}{3}\left[\mathbf{tr}\,\overline{\overline{\boldsymbol{R}}}\right]}{\bar{u}_\infty^2+\bar{v}_\infty^2+\bar{w}_\infty^2}}$$

C. Carlier.
Simulation du comportement d'hydroliennes : modélisation de l'influence de la turbulence ambiante et des effets d'interactions.
PhD thesis, Normandie Université, 2017.

Set parameters

- Area of influence of the ambient turbulence : volume V_0 ;
- Number of structures N / filling ratio $R_f = \frac{\frac{4}{3}\pi\lambda^3 N}{V_0}$;
- Variation on structure size $\sigma(\lambda)$: $\lambda_i \rightsquigarrow \mathcal{N}(\lambda, \sigma(\lambda)^2)$;
- Reynolds Stress Tensor $\overline{\overline{R}} = (R_{i,j})$: $R_{i,j} = \overline{(u_i - \overline{u}_i)(u_j - \overline{u}_j)}$.

Velocity fluctuation : Jarrin's SEM

$$\boldsymbol{u}_\infty = \overline{\boldsymbol{u}_\infty} + \tilde{\boldsymbol{u}} \quad \text{where} \quad \tilde{\boldsymbol{u}} = \sum_{k=1}^{N} \sqrt{\frac{V_0}{N}} \boldsymbol{c}^k F_{\boldsymbol{\lambda}^k}(\boldsymbol{x} - \boldsymbol{x}^k)$$

with :

$$c_i^k = \sum_{j=1}^{3} a_{i,j} \epsilon_{i,j}^k \quad \forall i \in \{1,2,3\} \quad \text{and} \quad \forall k \in [\![1, N]\!]$$

where :

$$\overline{\overline{A}} = (a_{i,j}) = \begin{pmatrix} \sqrt{R_{1,1}} & 0 & 0 \\ \frac{R_{2,1}}{a_{1,1}} & \sqrt{R_{2,2} - a_{2,1}^2} & 0 \\ \frac{R_{3,1}}{a_{1,1}} & \frac{R_{3,2} - a_{2,1} a_{3,1}}{a_{2,2}} & \sqrt{R_{3,3} - a_{3,1}^2 - a_{3,2}^2} \end{pmatrix}$$

and :

$$\overline{\overline{R}} = \overline{\overline{A}} \cdot \overline{\overline{A}}^T$$

T. S. Lund, X. Wu, and K. D. Squires.
Generation of turbulent inflow data for spatially-developing boundary layer simulations.
Journal of Computational Physics, 140 :233–258, 1998.

Divergence free formulation : Poletto's DFSEM

Velocity fluctuation

$$\tilde{\boldsymbol{u}}(\boldsymbol{x}) = \sqrt{\frac{1}{N}} \sum_{k=1}^{N} \boldsymbol{K}_\lambda \left(\frac{\boldsymbol{x} - \boldsymbol{x}^k}{\lambda} \right) \times \mathcal{R}(\boldsymbol{c}^k),$$

$$\boldsymbol{K}_\lambda(\boldsymbol{y}) = \frac{f_\lambda(|\boldsymbol{y}|)}{|\boldsymbol{y}|^3} \boldsymbol{y}.$$

Shape function

$$f_\lambda(y) = \sqrt{\frac{V_0}{\pi \lambda^3}} (\sin(\pi y))^2 y$$

if $y < 1$, 0 otherwise.

R. Poletto, T. Craft, and A. Revell.
A new divergence free synthetic eddy method for the reproduction of inlet flow conditions for les.
Flow, Turb. and Combustion, 91 :519–539, 2013.

Turbulent structure intensity

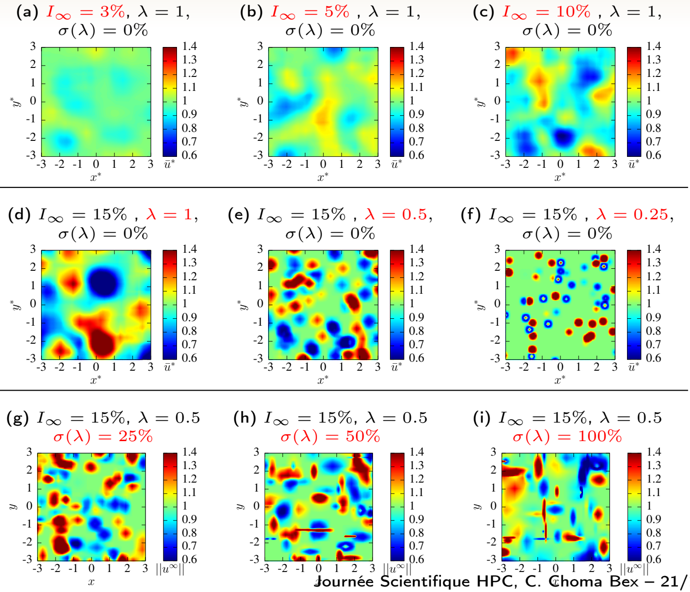
$$\boldsymbol{c}^k = \{C_i \epsilon_i\}_{i=1}^3,$$

$$C_i = \sqrt{\left(\sum_{j=1}^{3} \xi_j \right) - 2\xi_i},$$

ξ eigenvalues of $\overline{\overline{R}}$.

Outline

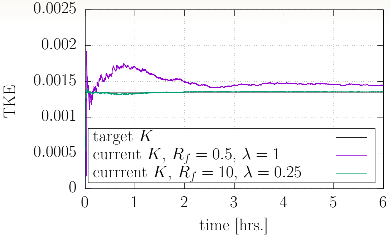
Example of Jarrin SEM velocity fields



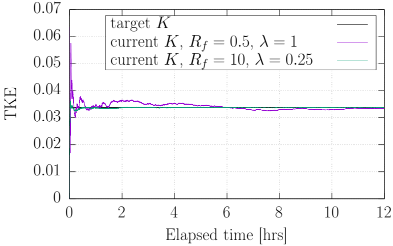
Reproduction of turbulent intensities

Turbulent Kinetic Energy

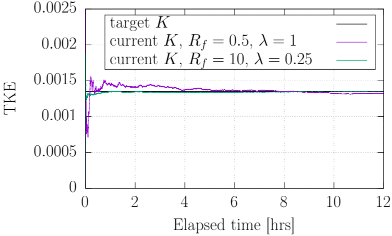
$$K = \frac{1}{2}\left(\sigma^2(u_\infty) + \sigma^2(v_\infty) + \sigma^2(w_\infty)\right)$$



DFSEM, $I_\infty = 3\%$

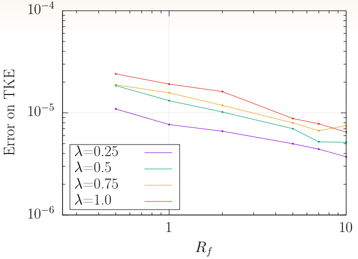


SEM, $I_\infty = 15\%$

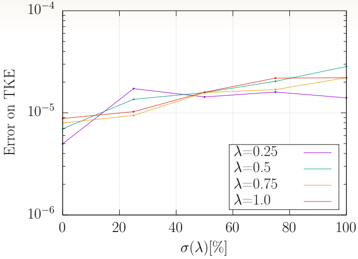


SEM, $I_\infty = 3\%$

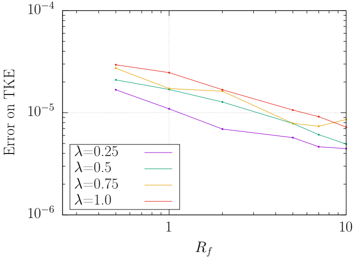
Convergence analysis



(a) Average errors / R_f, SEM, $I_\infty = 3\%$.



(b) Average errors / $\sigma(\lambda)$, SEM, $I_\infty = 3\%$.



(c) Average errors / R_f, DFSEM, $I_\infty = 3\%$.

C. Choma Bex, C. Carlier, A. Fur, G. Pinon, G. Germain, and E. Rivoalen.
A stochastic method to account for the ambient turbulence in lagrangian vortex computations.
Applied Mathematical Modelling, 88 :38 – 54, 2020.

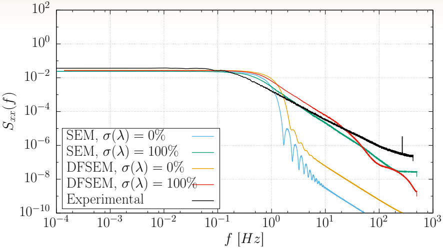
Turbulence properties ($I_\infty = 15\%$)

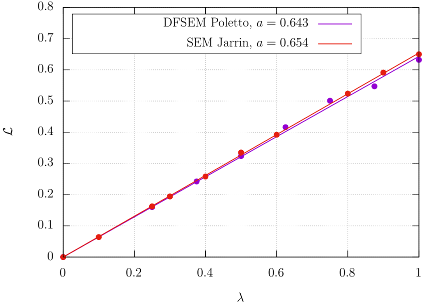
Power spectral density

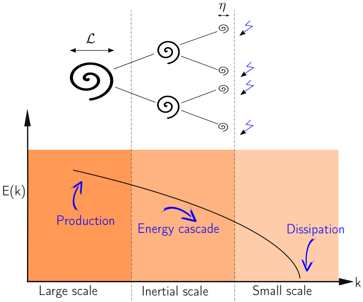
- Introduction of $\sigma(\lambda)$;
- $\lambda_i \quad \rightsquigarrow \quad \mathcal{N}(\lambda, \sigma(\lambda)^2)$.

Taylor macro-scale $\mathcal{L}$

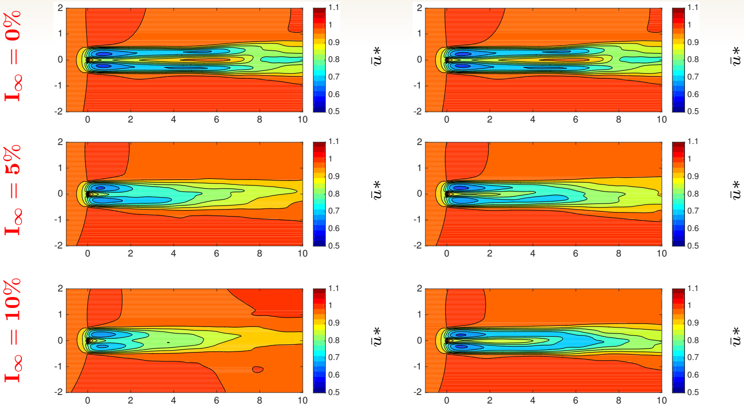
- $\mathcal{L}$ depends only on λ ;
- Linear relation between λ and $\mathcal{L}$.







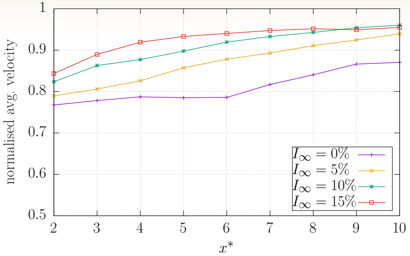
Influence on a turbine wake



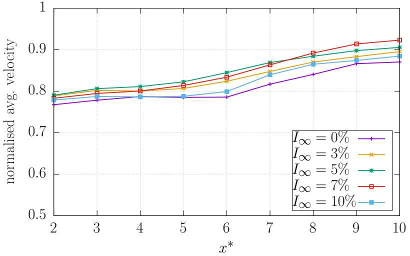
(a) SEM (b) DFSEM

C. Choma Bex, G. Pinon, M. Slama, B. Gaston, G. Germain, and E. Rivoalen.
Lagrangian vortex computations of turbine wakes : recent improvements using poletto's synthetic eddy method (SEM) to account for ambient turbulence.
Journal of Physics : Conference Series, 1618 :062028, sep 2020.

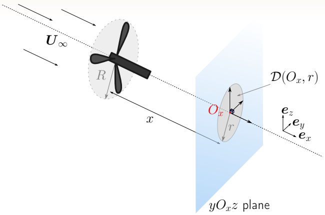
Integrated velocity



(a) SEM



(b) DFSEM



$$\frac{\int_{-R}^{R} |y| \overline{\boldsymbol{u}(x,y,0)} dy}{\pi R^2 \boldsymbol{U}_\infty}$$

Influence or turbulence intensity

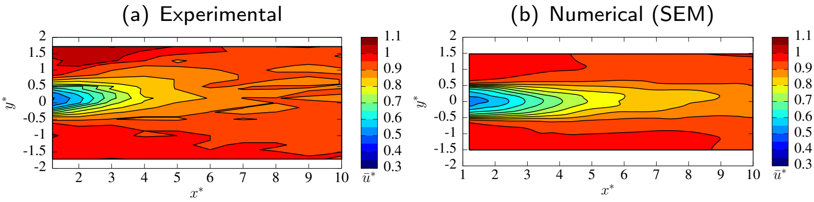
- Satisfyingly evidenced with SEM.
- Less apparent with DFSEM.

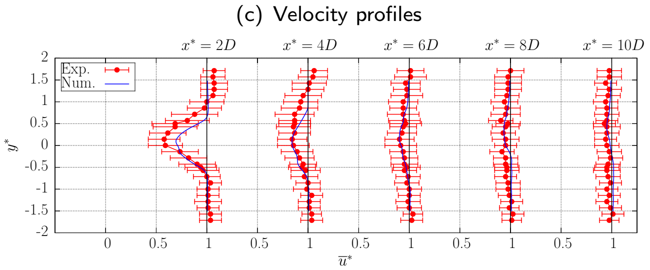
Outline

Outline

Comparison with experimental results

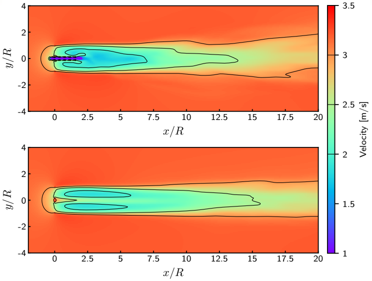
$$I_\infty = 15\%, \; TSR = 3.67.$$



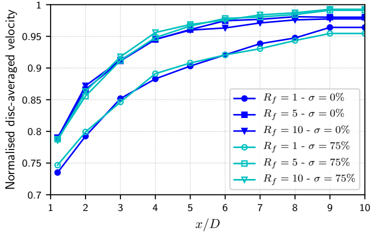


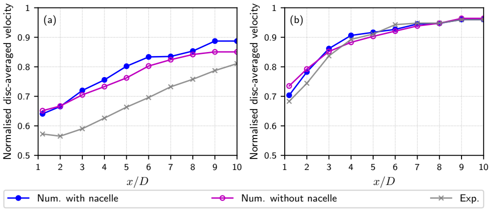
Influence of simulation and SEM parameters

$TSR = 3.67,\ I_\infty = 1.5\%\ R_f = 1.$



$TSR = 3.67,\ I_\infty = 15\%.$



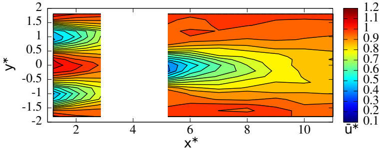


(a) $I_\infty = 1.5\%$ (b) $I_\infty = 15\%$

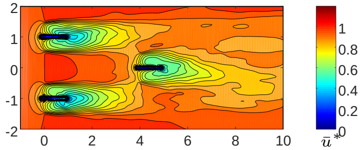
Comparison with experimental results
3 turbine configuration

$$I_\infty = 15\%,\ TSR = 3.5.$$

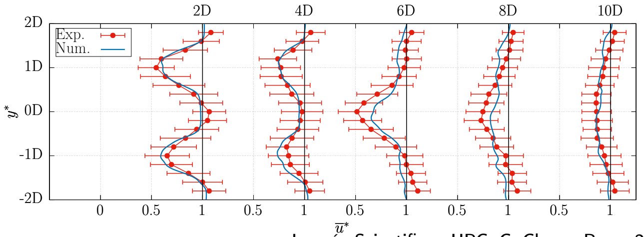
(a) Experimental



(b) Numerical (SEM)

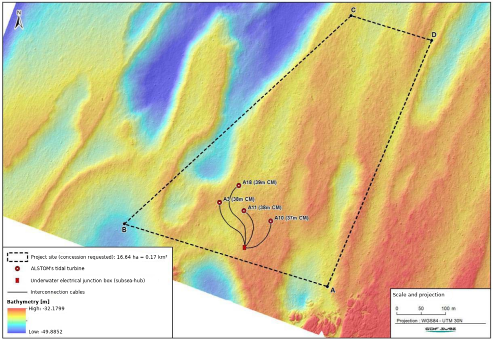


(c) Velocity profiles



Outline

NEPTHYD projected pilot farm



Autorité Environnementale, 2016.

Layout

- Alderney Race,
- 4 Alstom Oceade turbines,
- 3 on first row, 1 downstream.

Flow and turbine speed

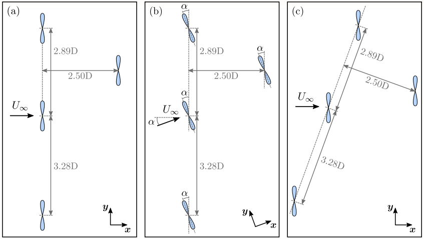
- Velocity $> 3.1m/s$,
- Optimal turbine TSR ~ 4.1,
- Flow direction $\sim 20^\circ$ from N.

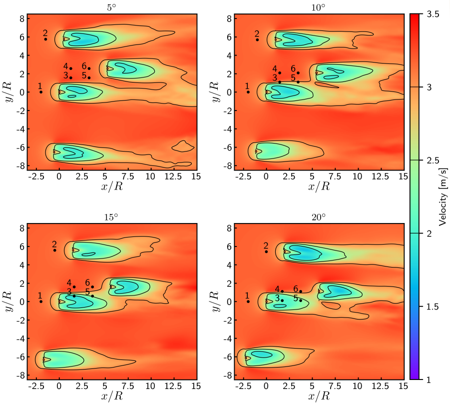
Turbulence conditions

- Turbulence intensity : $I_\infty = 10$ to 14%,
- Turbulent length scales $\mathcal{L}$: 18 and $30m$.

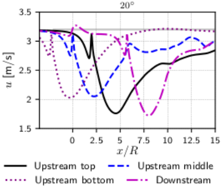
A. Sentchev, M. Thiébaut, and S. Guillou.
Turbulence characterization at tidal-stream energy site in Alderney Race.
CRC Press, 2020.

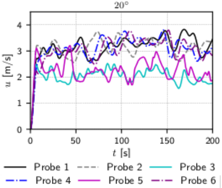
Impact of yaw





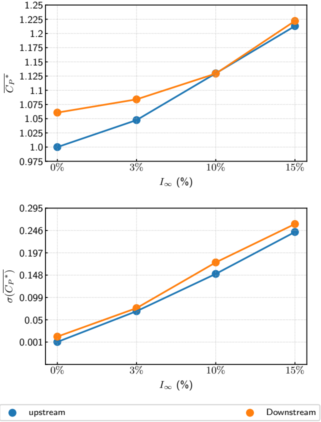
$$U_\infty = 3.2m/s \qquad TSR = 4.1$$
$$I_\infty = 10\% \qquad \mathcal{L} = 18m \Rightarrow \lambda = 27.5m$$
$$R_f = 229 \qquad \sigma(\lambda) = 75\%$$



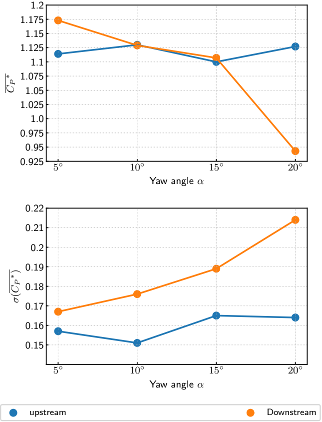


M. Slama, C. Choma Bex, G. Pinon, M. Togneri, and I. Evans.
Lagrangian vortex computations of a four tidal turbine array : An example based on the nepthyd layout in the alderney race.
Energies, 14 :3826–3839, 2021.

Time-averaged performances with BEM



(a) $\overline{C_p^*}$ and $\sigma(C_p^*)$, $\alpha = 10^\circ$



(b) $\overline{C_p^*}$ and $\sigma(C_p^*)$, $I_\infty = 10\%$

Outline

Conclusions

Integration of Synthetic Eddy Methods

- Influence of physical and numerical parameters studied on convergence and accuracy.
- Influence of physical and numerical parameters studied on turbine wakes.
- Physically advantageous alternative successfully implemented and validated in the absence of turbines.

Demonstration on a pilot farm configuration in the Alderney Race

- Successful simulation showcased on a full scale configuration with *in situ* conditions.
- Impact of yaw and wake interaction clearly evidenced.

Perspectives

Further considerations for simulation of realistic conditions

- Fluctuation of loads with ambient turbulence and turbine interaction.
- Velocity profile in incoming flow : vertical gradient and Stokes wave model.
- Control law for turbine rotation speed.
- Structural model for deformation and fatigue of blades.

Towards an open-source software distribution

- Multiple partnerships :
- Framework for open access.
- Framework for integration of user contributions.

Thank you for your attention.