Oral presentation | Fluid-structure interaction

Fluid-structure interaction-III

Mon. Jul 15, 2024 4:30 PM - 6:30 PM Room A

[3-A-03] Constrained Actuator Line Model with Controls in a Lattice Boltzmann framework for Floating Offshore Wind Turbine Simulations

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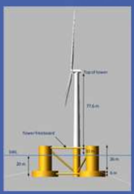
Keywords: Actuator Line Model, Lattice Boltzmann Method, Floating Offshore Wind Turbine, Fluid-Structure Interaction

Constrained Actuator Line Model with Controls in a Lattice Boltzmann framework for Floating Offshore Wind Turbine simulations



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Background

Onshore Wind Turbines

Pros	Cons
Mature	Saturating Market
Cheap	Limited by Terrain
Easy Maintenance	Visual and Noise Impact
	Low Installed Capacity

90% of installed wind power in 2020 are onshore wind turbine

IEA (2021). wind power, IEA, Paris, available from: https://www.iea.org/reports/wind-power

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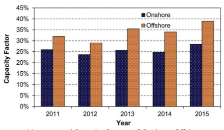
Background

"Fixed Bottom" Offshore Wind Turbines

- Sea is smoother than land
  - higher capacity factor
- Away from city
  - low noise and visual impact
- Can build larger wind turbines
  - Higher Installed Capacity

- 1000 GW potential for China
- Only feasible for shallow water (< 60m)
- 80% of offshore wind not suitable



Mean annual Capacity Factors of Onshore-Offshore wind installations in the UK

Kaldellis, J.K., Apostolou, D., 2017, Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart, *Renewable Energy*, 108, 72-84

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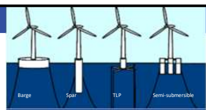
Floating Offshore Wind Turbines

- Mount tower on a floating platform
- Solve water depth limitation



Salic et al. (2019)

1 Ballast-stabilized

SPAR type

Stabilization achieved by having a ballast located at the bottom of the platform to shift the center of gravity below the center of buoyancy

2 Mooring-stabilized

Tension Leg Platform (TLP) type

Uses high tension mooring lines to generate the righting moment when the structure is tilted

3 Buoyancy-stabilized

Barge type
Semi-submersible type

Stabilization achieved by having a large water-plane area

Salic, T., Charpentier, J.F., Benbouzid, M., Le Boulluec, M., (2019), Control Strategies for Floating Offshore Wind Turbine: Challenges and Trends, *MDPI Electronics*, 8, 1185

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Background

How to model FOWTs?

Engineering Tools

- OpenFAST / FAST by NREL
- SIMO-Riflex by Sintef Ocean
- HAWC2 by Technical University of Denmark
- 3Dfloat by IFE
- DeepCwind by University of Maine
- Bladed by DNV-GL

- Aerodynamics: Quasi-static Blade Element Momemtum (BEM) Theory
- Hydrodynamics: Potential Flow Theory
- Not very accurate

Scaled Experiment

- Conducted in wind turnels with water tank with wave generator
- Need special rotor design to address Reynolds number difference
- Used to validate numerical models/ Engineering models
- Costly

Coulling et al. (2013)

Computational Fluid Dynamics

- Directly include all physical effects (flow viscosity, hydrostatic, wave diffraction, radiation, wave run-up, slamming, etc.)
- High fidelity

- Computational costly if fully-resolved
- Underestimate the hydrodynamic impact to FOWT

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Framework

OC4 Semi-submersible platform with NREL 5MW Reference WT: Rigid Body Dynamics

- **Aerodynamics: Entropic LBM with Actuator Line Model**
- **Hydrodynamics: Potential Flow with Morison's Equation**

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Lattice Boltzmann Method: BGK collision model

1. Lattice Boltzmann equation: $f_i(t+\Delta t, x+\Delta x) - f_i(t,x) = \Omega_i(t,x)$
2. BGK collision operator: $\Omega_i^{BGk} = -\frac{\Delta t}{\tau}(f_i - f_i^{eq})$
3. Equilibrium distribution function: $f_i^{eq} = \rho w_i \left[1 + \frac{\boldsymbol{u}\cdot\boldsymbol{e}_i}{c_s^2} + \frac{(\boldsymbol{u}\cdot\boldsymbol{e}_i)^2}{2c_s^4} - \frac{\boldsymbol{u}\cdot\boldsymbol{u}}{2c_s^2}\right]$
4. D3Q27 scheme: $w_0 = 8/27, w_{1-6} = 2/27, w_{7-18} = 1/54, w_{19-2} \ = 1/126$

At high Reynolds number conditions (when τ is close to 0.5), LBGK suffers from instability, limiting the use of LBGK to low Reynolds number flow

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Lattice Boltzmann Method: Entropic collision model

1. ELBM introduces a discrete entropy functional and enforcing an H-theorem
2. H-function to calculate Entropy: $H[\{f_i\}](t) = \left\langle f, ln\left[\frac{f}{w}\right]\right\rangle$
3. Equilibrium distribution function: $f_i^{eq} = \rho w_i \prod_{y=1}^{3}\left[2 - \sqrt{(u_\alpha/c_s)^2+1}\right]\left[\frac{2u_\alpha + \sqrt{(u_\alpha/c_s)^2+1}}{1-u_\alpha}\right]^{c_{i\alpha}}$
4. Entropic collision operator: $\Omega_i^{ELBM} = \alpha\beta(f_i^{eq} - f_i) = \alpha\beta\Delta_i^{ELBM}$
   $\beta = \frac{\Delta t}{\left(\frac{2v}{c_s^2} + \Delta t\right)}$
5. Newton-Raphson method: $\alpha_{n+1} = \alpha_n - \frac{g(a_n) - g(0)}{g\prime(a_n)}$
   $\alpha_{min} = 1.1$

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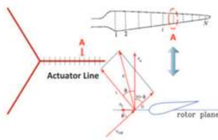
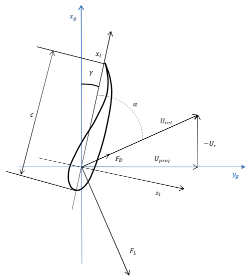
Actuator Line Model



α	Angle of Attack of the blade element
γ	Sum of twist angle and pitch of the blade element
c	Chord length
$\boldsymbol{U_r}$	Velocity of blade element due to rotation
$\boldsymbol{U_{proj}}$	Projected wind velocity (U_f) on the airfoil plane
$\boldsymbol{U_{rel}}$	Reletive Velocity
F_L/F_D	Lift / Drag forces acting on the blade element
x_g, y_g	Global axis for blade element
x_l, y_l	Local axis for blade element



Sorensen, J.N., Shen, W.Z. (2002) Numerical Modeling of Wind Turbine Wakes

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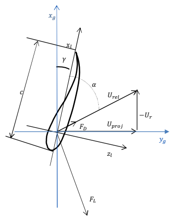
Actuator Line Model

1. Obtain Angle of Attack from relative velocity (U_f obtainted from LBM);
   $U_{proj} = U_f - (U_f \cdot y_l)\cdot y_l$
   $U_{rel} = U_{proj} - U_r$
2. Obtain C_L and C_d data from tabulated airfoil data using AOA;
   $\alpha = cos^{-1}\left(\frac{U_{rel}\cdot x_l}{\widehat{U_{rel}}\cdot \hat{x_l}}\right)$
3. Calculate lift and drag forces F_l and F_d using C_L and C_d ;
   $F_l = 0.5 f_{loss}\rho \boldsymbol{u_{rel}}^2 cw(C_L\boldsymbol{e_L})$
   $F_d = 0.5 f_{loss}\rho \boldsymbol{u_{rel}}^2 cw(C_D\boldsymbol{e_D})$
4. Use the lift and drag forces to obtain torque, sum up torque from all blade elements to obtain the external torque applied to the rotor;
   $r_i = pos_i - pos_r$
   $\tau_{ext} = \sum_0^{i=n} r_i\cdot(F_{li} + F_{di})$
5. Find lift and drag forces for all blade elements to obtain the external force applied to the rotor;
   $F_{ext} = \sum_0^{i=n} F_{li} + F_{di}$
6. Feed the external forces and torques to the constraint system and Feed the forces on each blade element to LBM



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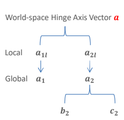
Rigid Body Constraint System

WT is formed by 6 rigid bodies: rotor, nacelle, tower, and platform consists of three buoys

Hinge Joint only allow relative rotation between two rigid bodies around a single axis α
Fixed Joint do not allow any relative motion between two rigid bodies.



$C_{trans}(S) = x_2 + r_2 - x_1 - r_1 = 0$ — Translation constraint → Removes 3 DoF

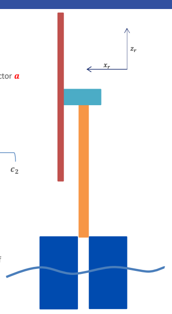
$C_{rot}(S) = \begin{pmatrix} a_1\cdot b_2 \\ a_1\cdot c_2 \end{pmatrix} = 0$ — Hinge Rotation constraint → Removes 2 DoF

$C_{rot}(S) = \begin{pmatrix} \theta_{2x} - \theta_{1x} \\ \theta_{2y} - \theta_{1y} \\ \theta_{2z} - \theta_{1z} \end{pmatrix} = 0$ — Fixed Rotation constraint → Removes 3 DoF

$\theta_{ix}, \theta_{iy}, \theta_{iz}$ are the orientation angles of the body around x, y, z axis

Hinge Joint applied to
- rotor - nacelle : Hinge axis along x_r direction
- nacelle - tower: Hinge axis along z_r direction

Fixed Joint applied to platform - tower



Chappuis, D., (2013), Constraints Derivation for Rigid Body Simulation in 3D

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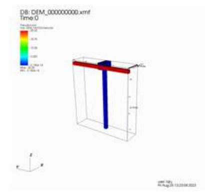
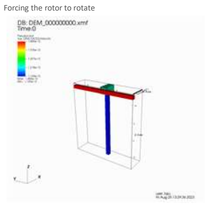
Constraint System

DEM particles used to visulize the rotation

Forcing the nacelle to rotate



Forcing the rotor to rotate



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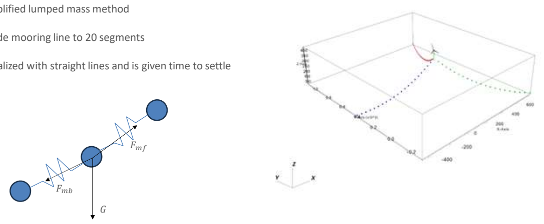
Mooring

Simplified lumped mass method

Divide mooring line to 20 segments

Initialized with straight lines and is given time to settle



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Control Systems

Generator Torque Control

Generator torque is computed as a tabulated function of the generator speed, and is divided into 5 control regions:

Region 1:

$$\tau_{gen} = 0$$

Region 1 1/2:

$$\tau_{gen} = \alpha_{1.5}(\omega - \omega_{cut\ in})$$

Region 2:

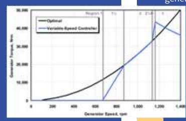
$$\tau_{gen} = K\omega^2$$

Region 2 1/2:

$$\tau_{gen} = \alpha_{2.5}(\omega - \omega_{sync})$$

Region 3:

$$\tau_{gen} = \frac{P_{rated}}{\omega}$$



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Blade Pitch Control

in Region 3, the blade pitch commands are computed using gain scheduled proportional-integral control on the speed error between the filtered generator speed and the rated generator speed:

$$\Delta\theta = K_P N_{Gear} \Delta\Omega + K_I \int_0^t N_{Gear} \Delta\Omega dt$$

$$K_P = \frac{2 I_{Drivetrain} \Omega_0 \zeta_\varphi \omega_{\varphi n}}{N_{Gear}\left(-\frac{\partial P}{\partial \theta}\right)}$$

$$K_I = \frac{I_{Drivetrain} \omega_{\varphi n}{}^2}{N_{Gear}\left(-\frac{\partial P}{\partial \theta}\right)}$$

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Jonkman et al., (2009), Definition of a 5-MW Reference Wind Turbine for Offshore System Development

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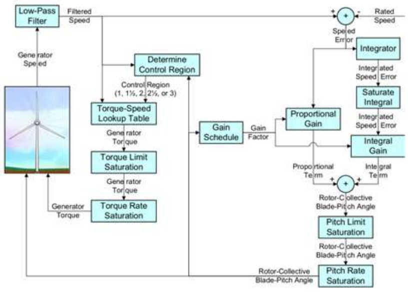
Control Systems

$$\tau_{rotor} = \tau_{ext} - N_{Gear} \tau_{gen}$$



Jonkman et al., (2009), Definition of a 5-MW Reference Wind Turbine for Offshore System Development

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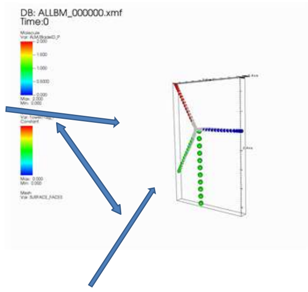
Results

Wind turbine under changing wind direction on Y axis

Nacelle rotates with hinge axis along z direction
Rotor rotates along x direction

The implement of constraints means now the ALM can react to wind from different directions by rotating the nacelle.



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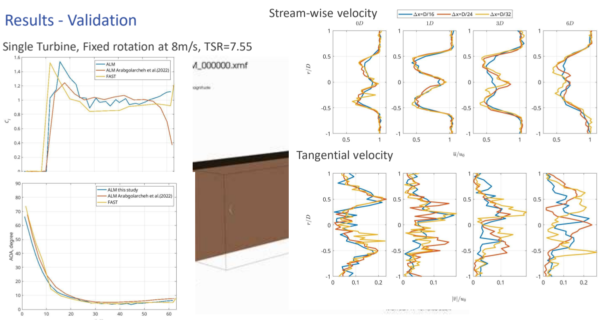
Results - Validation

Single Turbine, Fixed rotation at 8m/s, TSR=7.55



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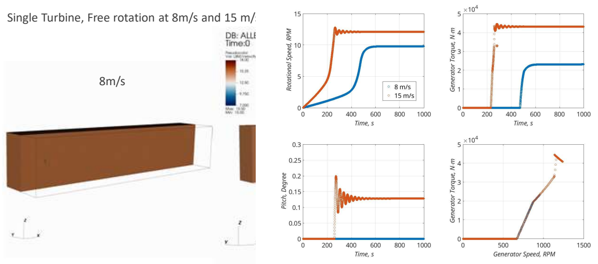
Results

Single Turbine, Free rotation at 8m/s and 15 m/



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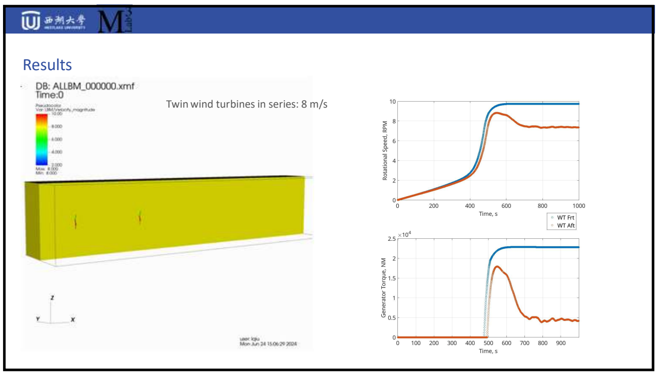
Results
DB: ALLBM_000000.xmf
Time:0
Twin wind turbines in series: 8 m/s
Rotational Speed, RPM
Time, s
WT Frt
WT Aft
Generator Torque, NM
Time, s

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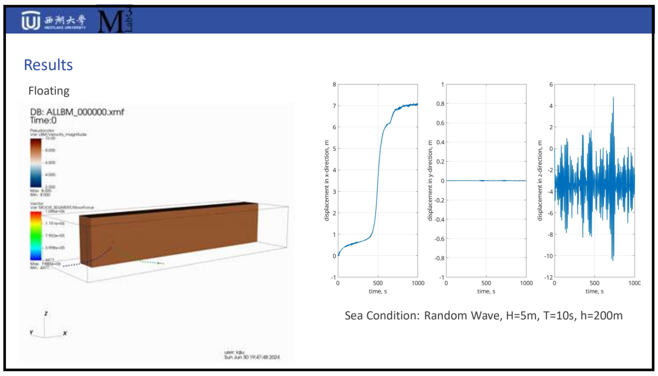
Results
Floating
DB: ALLBM_000000.xmf
Time:0
time, s
time, s
time, s
Sea Condition: Random Wave, H=5m, T=10s, h=200m

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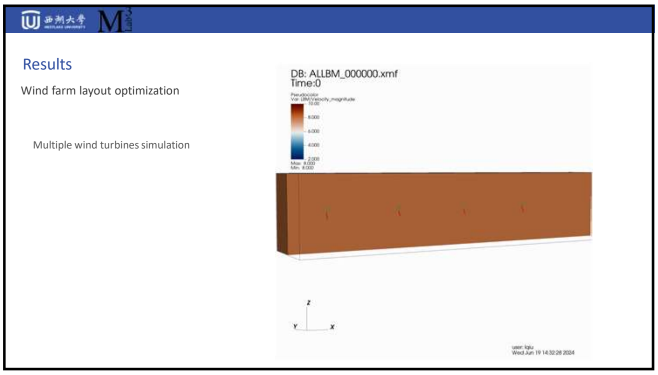
Results
Wind farm layout optimization
Multiple wind turbines simulation
DB: ALLBM_000000.xmf
Time:0

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Thank you!

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