Numerical simulation of multi-rotor diffuser augmented wind turbine system using the actuator line method in PyFR solver

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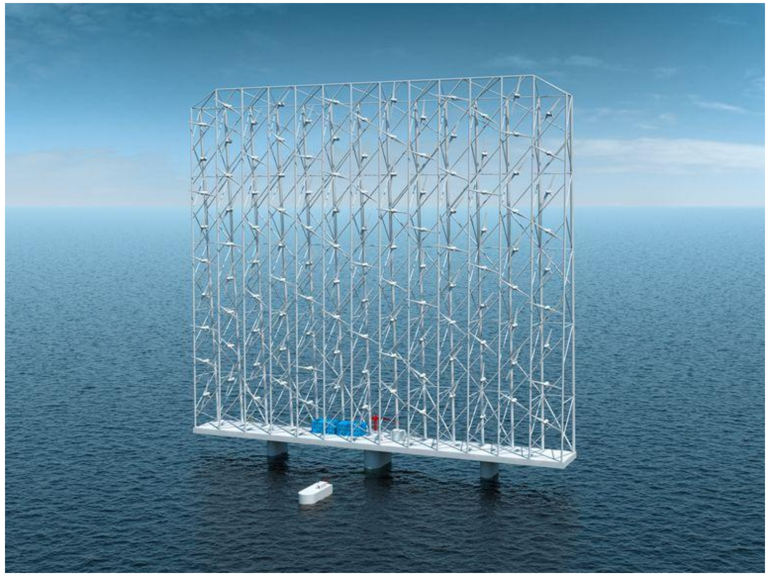
Introduction

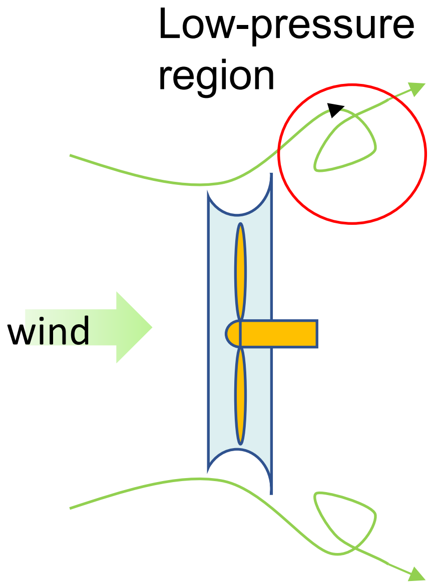
Multi-rotor diffuser-augmented wind turbines system



Multi-rotor system (MRS)

Advantages:

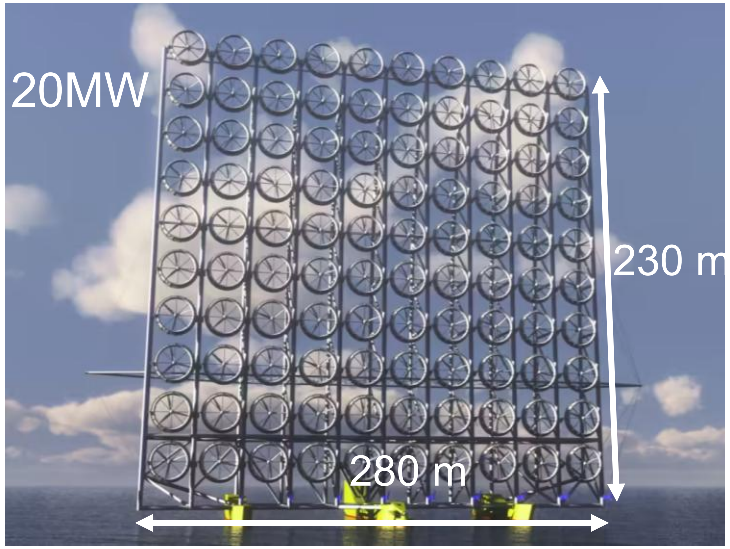
- **Cost efficiency**
- **Maintainability**
- **Scalability**



Diffuser augmented wind turbine (DAWT)

Advantages:

- **Increased efficiency**
- **Compact design**



Novel floating offshore multi-rotor DAWT system

Challenges:

- **Blockage effect**
- **Wake interactions**

Numerical Method

Actuator Line Method -- Blade model

The incompressible Navier–Stokes equation

$$\frac{\partial V}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \upsilon \nabla^2 \vec{V} + \vec{f}$$

The blade element body force

$$\vec{f} = \frac{1}{2} \rho U_{rel}^2 w_b c_b \left(C_{l,b} \vec{e_l} + C_{d,b} \vec{e_d} \right) \cdot F_{tip}$$

$C_{l,b}$ and $C_{d,b}$ are the lift and drag coefficients

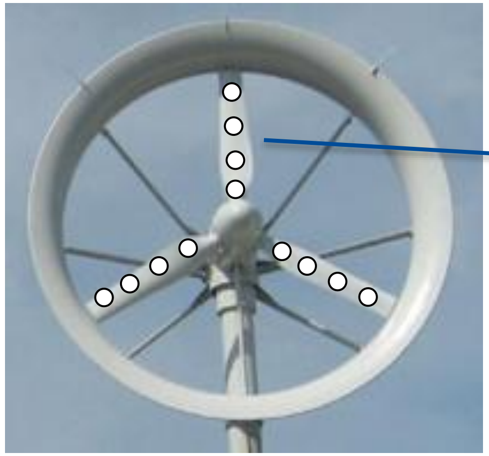
$C_l, C_d = f(\alpha, Re)$

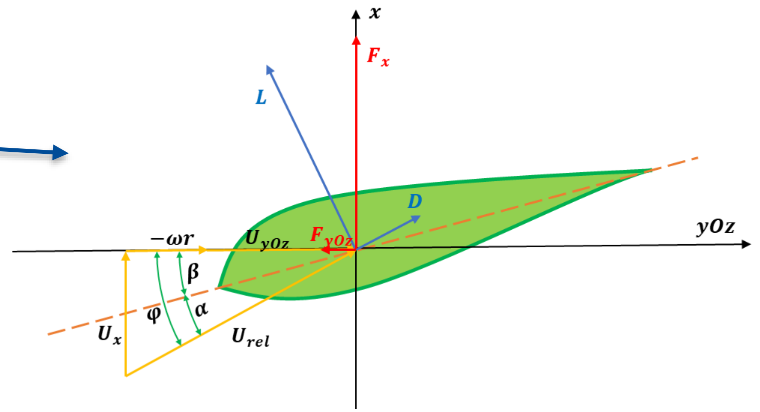
$\vec{e_l}$ and $\vec{e_d}$ are unit vector in the lift and drag directions

w is the segment width, c is the chord length

U_{rel} is the local relative inflow velocity

F_{tip} is the tip loss correction





The velocity triangle of the cross-sectional blade element

Projection function for blade element

$$g_{iso}(x, y, z) = \frac{1}{\varepsilon^3 \pi^{3/2}} \exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}{\varepsilon^2}\right)$$

ε is the Gaussian projection width

Numerical Method

Actuator Line Method -- Diffuser model

The diffuser element body force

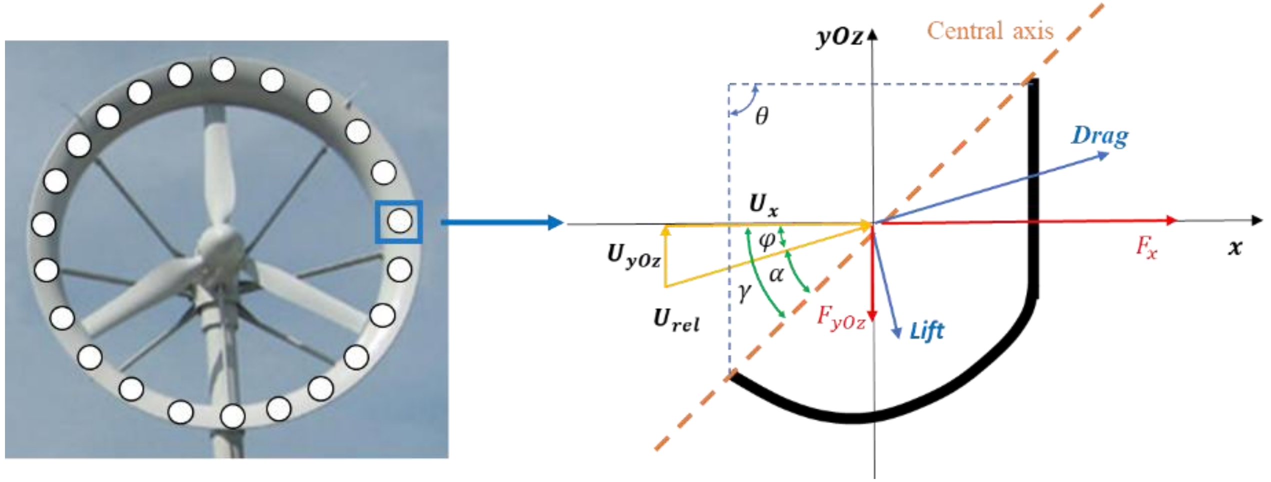
$$\vec{f} = \frac{1}{2}\rho U_{rel}^2 w_d c_d \left(C_{l,d}\vec{e_l} + C_{d,d}\vec{e_d}\right)$$

$C_{l,d}$ and $C_{d,d}$ are the lift and drag coefficients of the diffuser structure

$\vec{e_l}$ and $\vec{e_d}$ are unit vectors in the lift and drag directions

w_d is the width of the diffuser segment, c_d is the chord length

U_{rel} is the local relative inflow velocity



The velocity triangle of the cross-sectional diffuser element

Local attack angle

$$\alpha = \varphi - \gamma$$

γ is the local tilt angle

$$\varphi = arctan\left(\frac{U_{yOz}}{U_x}\right)$$

Numerical Method

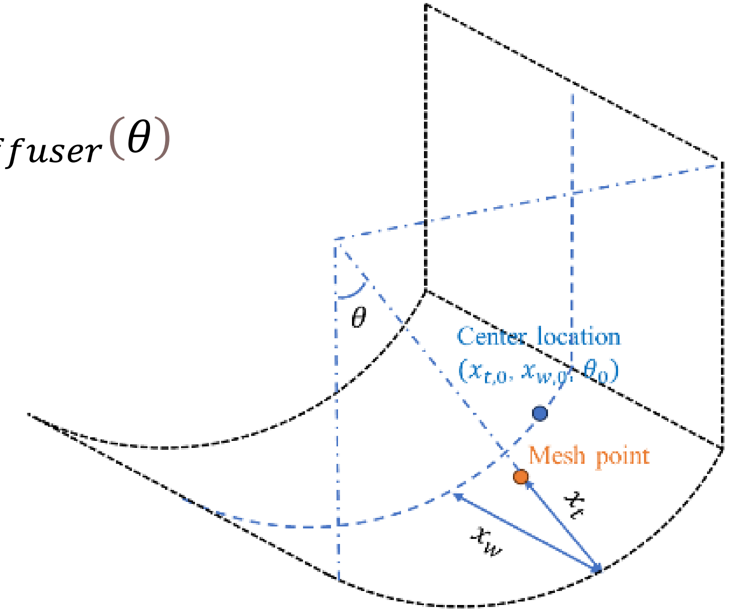
Actuator Line Method -- Diffuser model

Projection function

$$g_{diffuser}(x_t, x_w, \theta) = C \cdot exp\left(-\frac{(x_t - x_{t,0})^2}{\varepsilon_t^2} - \frac{(x_w - x_{w,0})^2}{\varepsilon_w^2}\right) \cdot g_{diffuser}(\theta)$$

x_t, x_w and θ are the thickness, width, and azimuthal coordinate directions, respectively

$\varepsilon_t = a_t t$ and $\varepsilon_w = a_w w$ represent the Gaussian widths in the radial and tangential directions



The schematic diagram of force projection

Normalization factor

$$C = \left[2\pi\varepsilon_t\varepsilon_r \cdot \int_{-\frac{\pi}{2}}^{0} f(\theta)\, d\theta\right]^{-1}$$

Force magnitude function

$$g_{diffuser}(\theta) = \frac{2}{\omega}\phi\left(\frac{\theta-\theta_0}{\omega}\right)\Phi\left(\tau\left(\frac{\theta-\theta_0}{\omega}\right)\right)$$

$$\phi(x) = \frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}} \qquad \Phi(x) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x}{\sqrt{2}}\right)\right]$$

θ_0, ω and τ are the center location, scale and shape parameter, respectively

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Numerical Method

PyFR Slover

The Flux Reconstruction approach is a unifying framework for high-order schemes.

Advantage

1. High accuracy--Achieving more precise results with a smaller number of grids

2. High efficiency--Only requires neighboring cells to update physical quantities within a cell

PyFR

PyFR: An open source framework for solving advection–diffusion type problems on streaming architectures using the flux reconstruction approach☆

CrossMark

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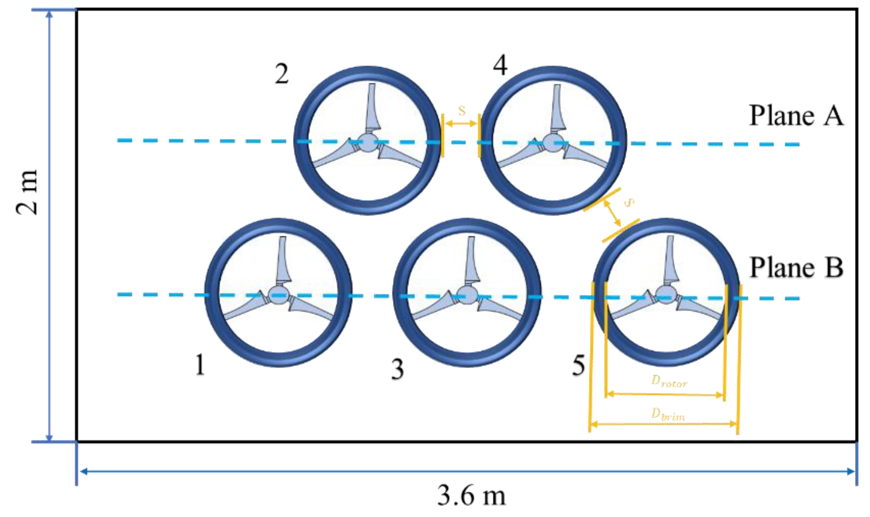
https://doi.org/10.1016/j.cpc.2014.07.011

Results and discussion

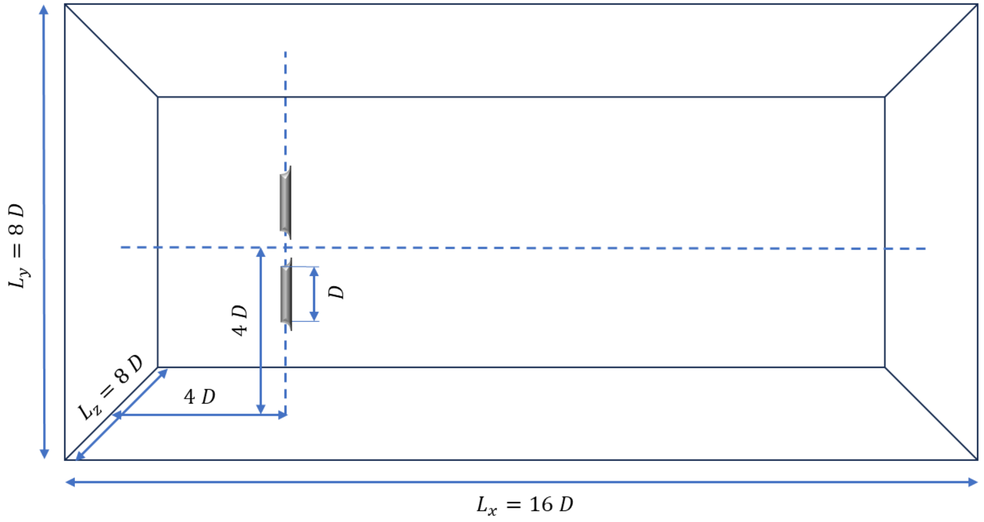
5-rotor DAWT system

Parameter of the multi-rotor system experiment

Parameter	Value
Rotor diameter (D_{rotor})	0.5 m
Brim diameter (D_{brim})	0.669 m
Tip speed ratio (TSR)	4
Inflow speed	6 m/s
Lens shape	Cii type brim 10%
Gap ratio (S)	$0.2D_{rotor}$



Schematic diagram of 5-rotor system experiment



Side view of the computational domain

Results and Analysis

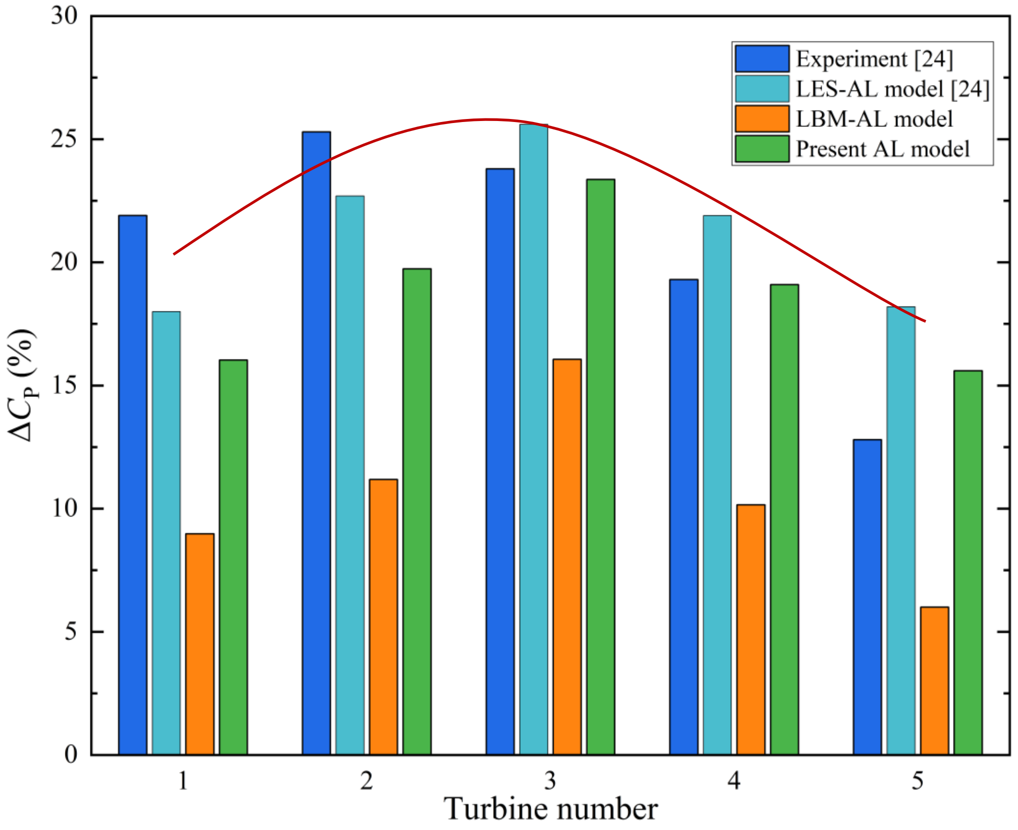
5-rotor DAWT system

$$\Delta C_{P,i} = \frac{C_{P_i}}{C_{P,standalone}} - 1$$

$$C_P = \frac{P}{\frac{1}{2}\rho A_{D_{brim}} U_\infty^3}$$

The results demonstrate that the AL-PyFR(DAWT) model accurately predicts ΔC_P for each rotor in the 5-rotor system.

This asymmetry arises because all rotors rotated in the same direction.

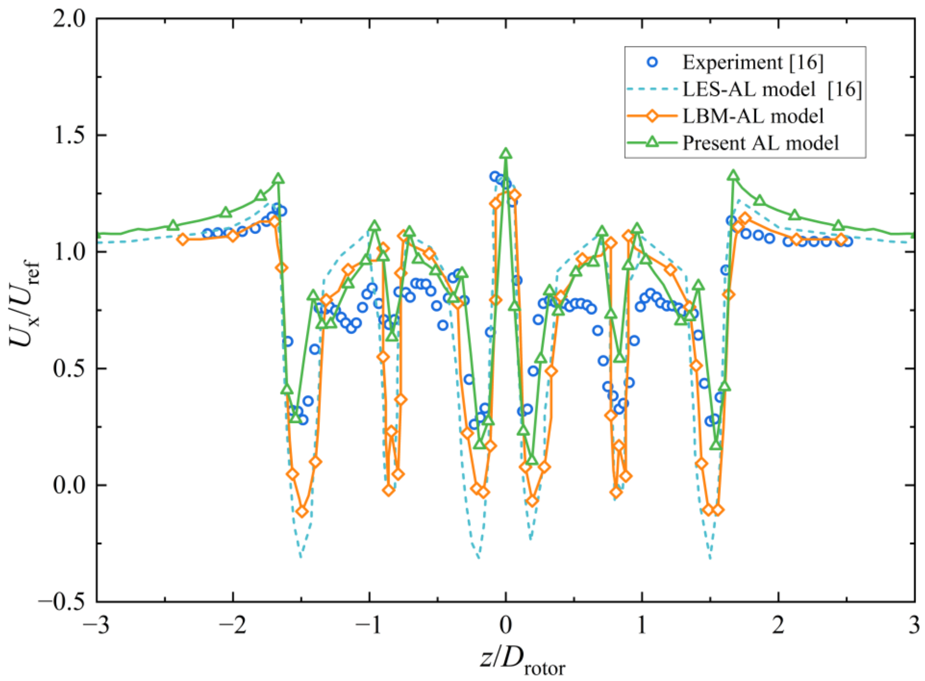


ΔC_P comparison of each rotor in the 5-rotor system

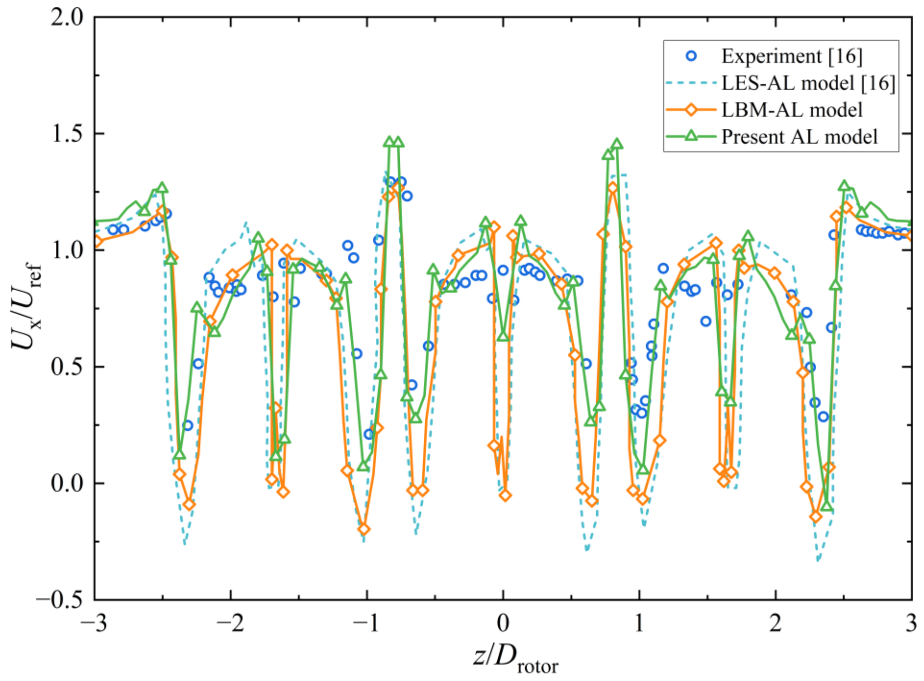
3. Results and Analysis

5-rotor DAWT system

The AL-PyFR(DAWT) model wake velocity profiles align well with both experiment result and the predictions from other numerical models.



Mean wake velocity profile at plane A

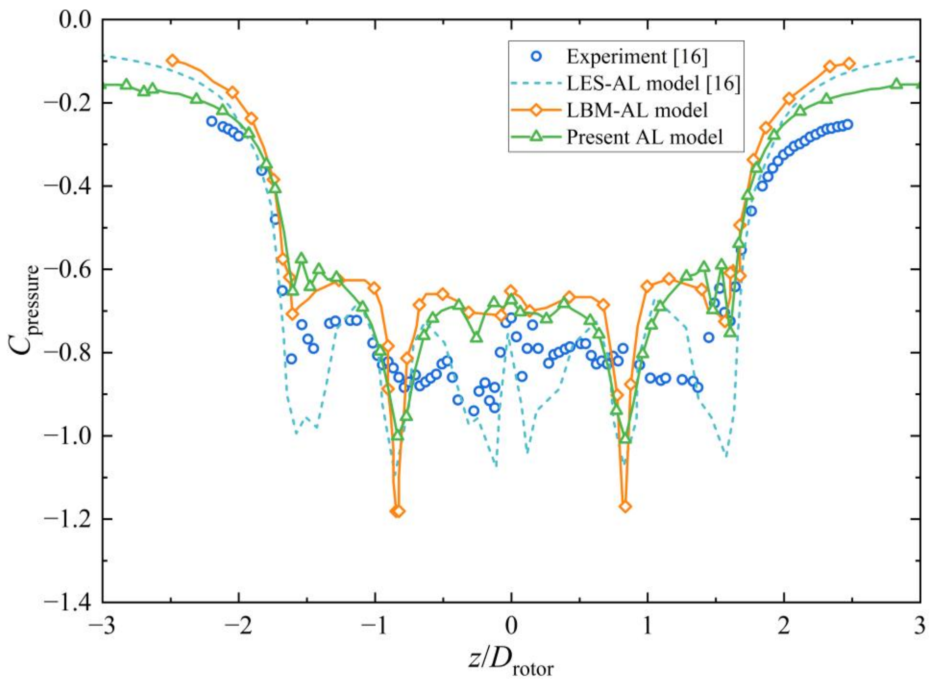


Mean wake velocity profile at plane B

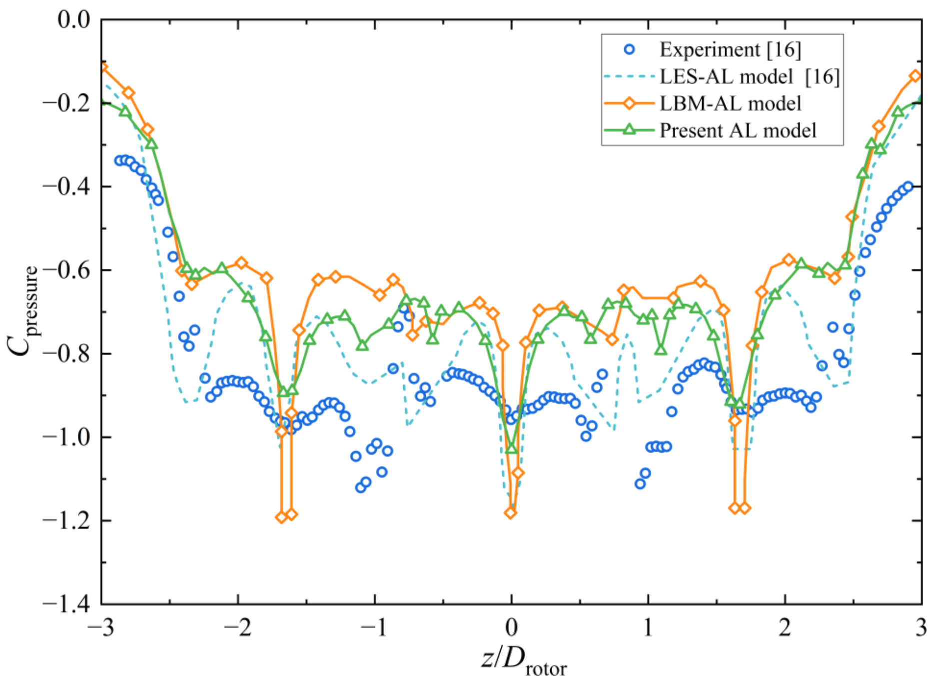
Comparison of the mean wake velocity $x = 0.4D_{rotor}$

3. Results and Analysis

5-rotor DAWT system



Mean pressure profile at plane A



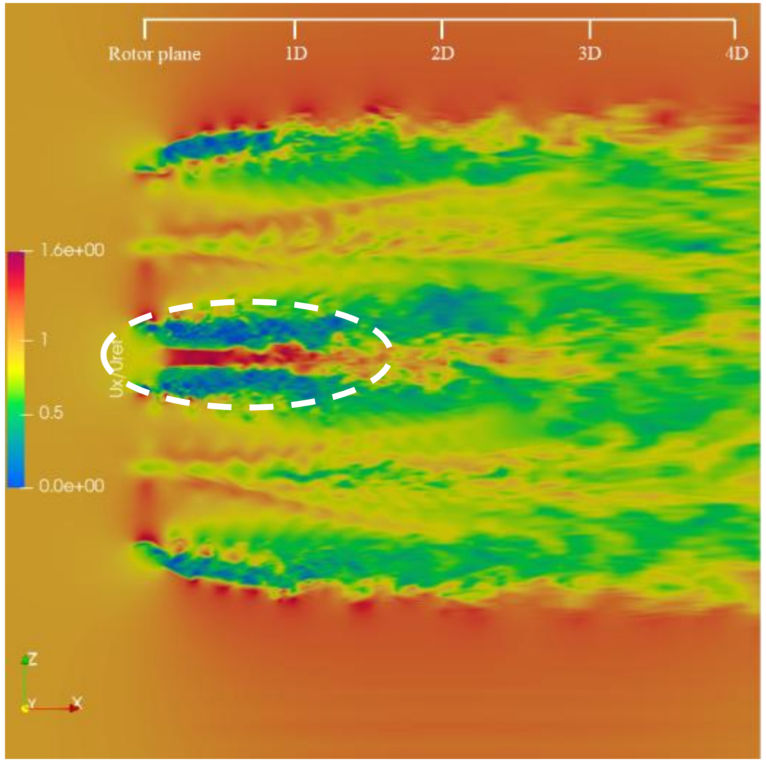
Mean pressure profile at plane B

Comparison of the mean wake pressure $x = 0.4D_{rotor}$

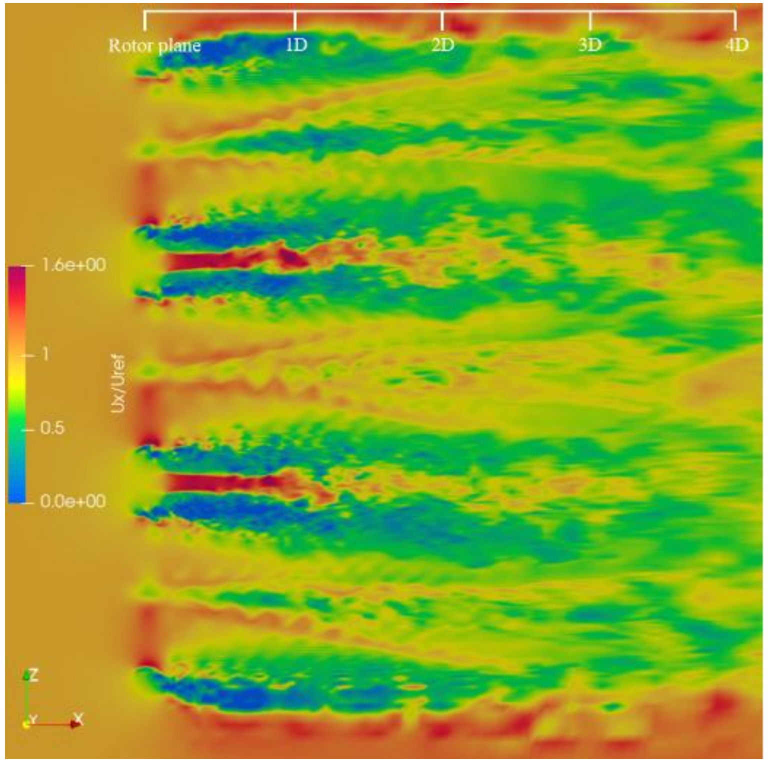
3. Results and Analysis

5-rotor DAWT system

This high-speed region arises from the blockage effect among the rotors, resulting in overall higher wake speeds compared to a single rotor case.



Plane A



Plane B

Contours of the instantaneous streamwise velocity in the $x - y$ plane

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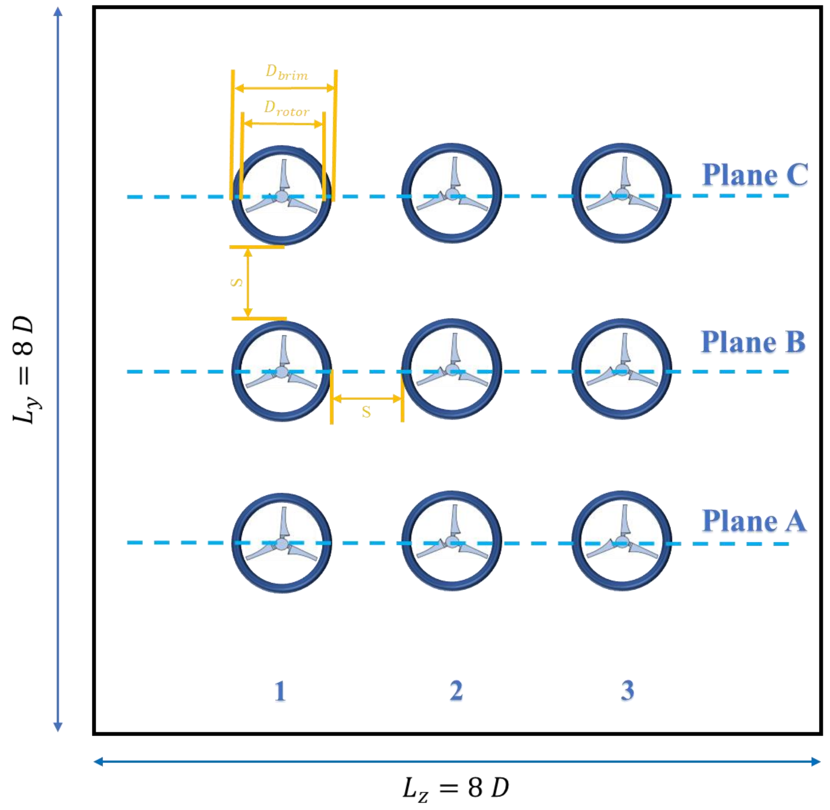
3. Results and Analysis

9-rotor DAWT system

The focus is to investigate the influence of rotor spacing and TSR on both aerodynamic efficiency and structural stability.

Parameter of the 9-rotor DAWTs system

Parameter	Value
Rotor diameter (D_{rotor})	1 m
Brim diameter (D_{brim})	1.35 m
Tip speed ratio (TSR)	3~5
Inflow speed	10 m/s
Lens shape	Cii type brim 10%
Gap ratio (S)	0.05~0.4



Cross-section of the computational domain at rotor plane

3. Results and Analysis

9-rotor DAWT system

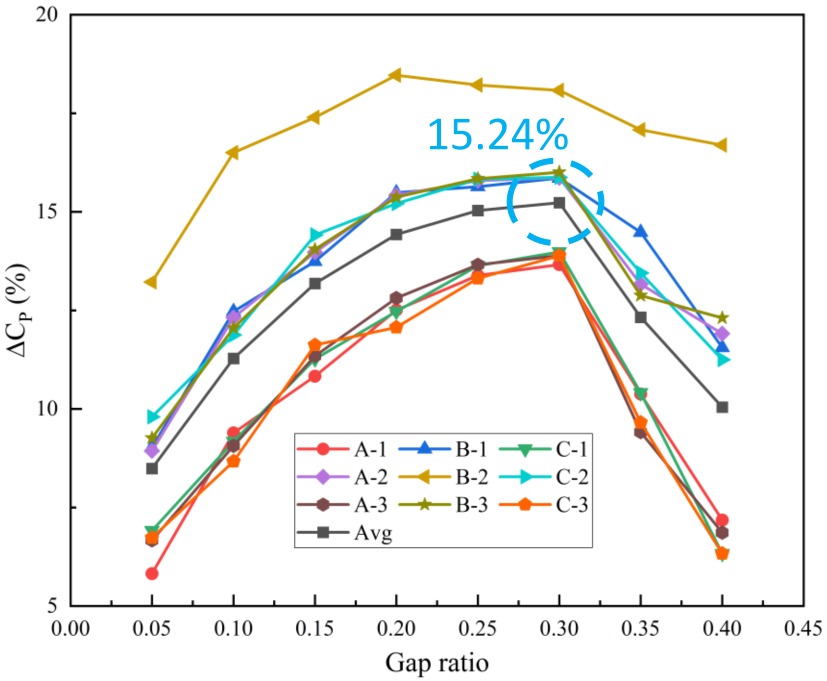
$$\Delta C_{T,\mathrm{rotor},i} = \frac{C_{T,rotor,\,i}}{C_{T,\mathrm{rotor},\,standalone}} - 1$$

$$\Delta C_{T,\mathrm{brim},i} = \frac{C_{T,brim,\,i}}{C_{T,\mathrm{brim},\,standalone}} - 1$$

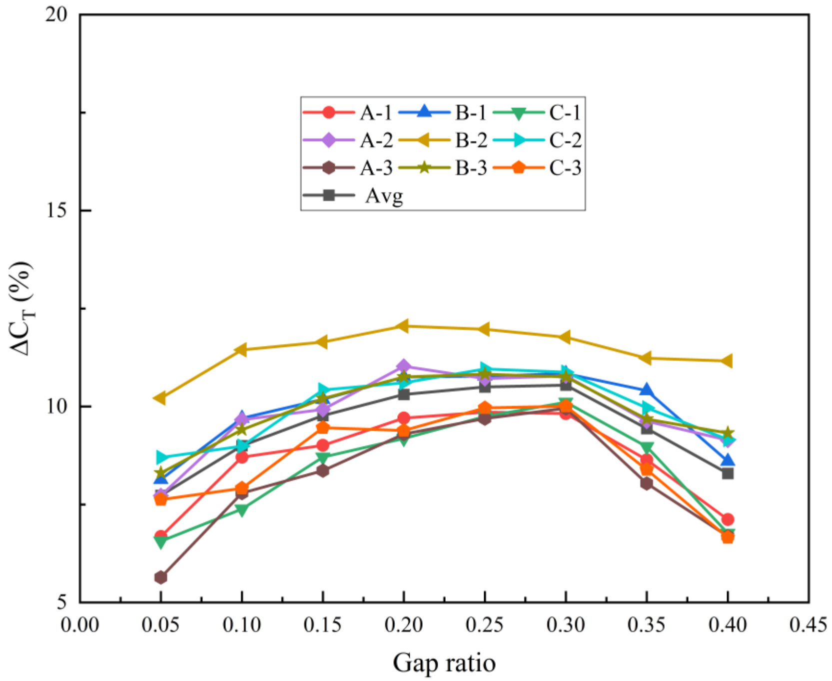
The central rotor demonstrating the highest efficiency and lowest sensitivity to spacing.

$$C_{T,rotor} = \frac{T_{blade}}{\frac{1}{2}\rho A_{D_{rotor}} U_\infty^2}$$

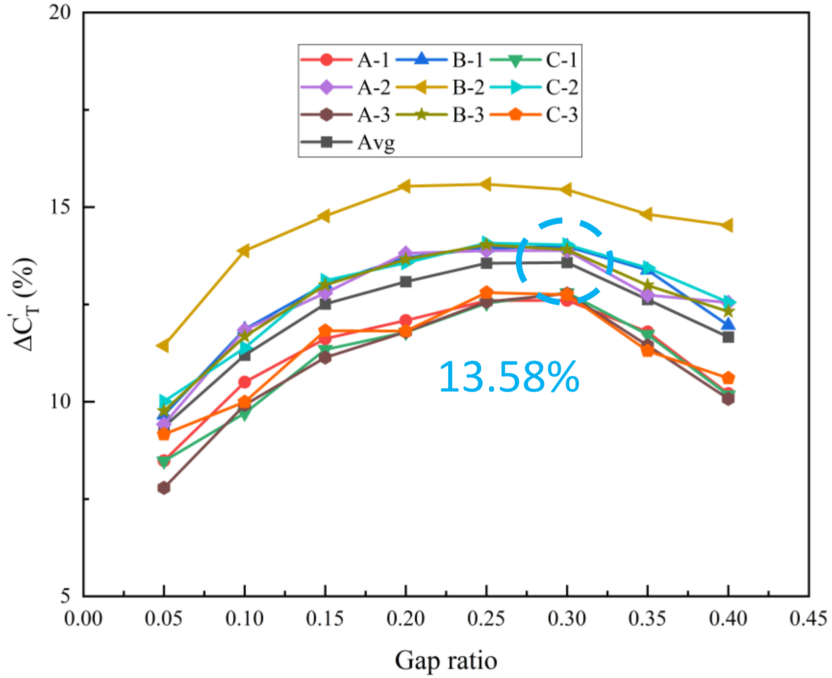
$$C_{T,brim} = \frac{T_{blade} + T_{diffuser}}{\frac{1}{2}\rho A_{D_{brim}} U_\infty^2}$$



Variation of ΔC_P under different gap ratio



Variation of ΔC_T under different gap ratio

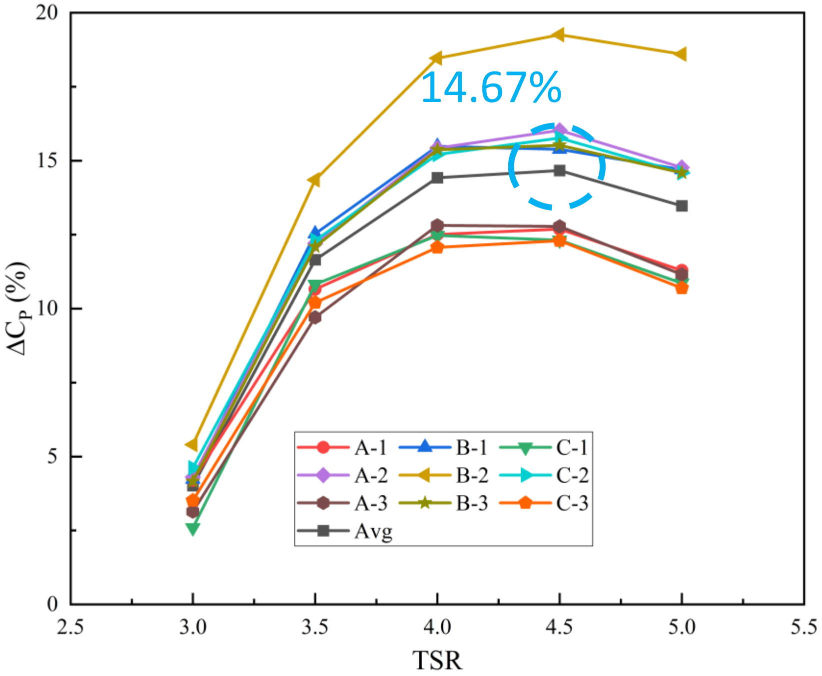


Variation of $\Delta C_T'$ under different gap ratio

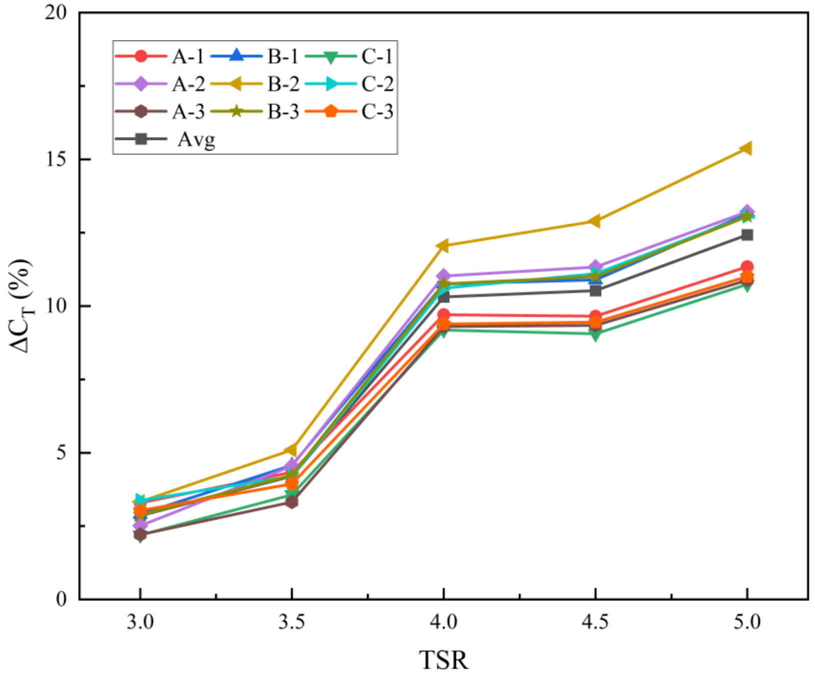
3. Results and Analysis

9-rotor DAWT system

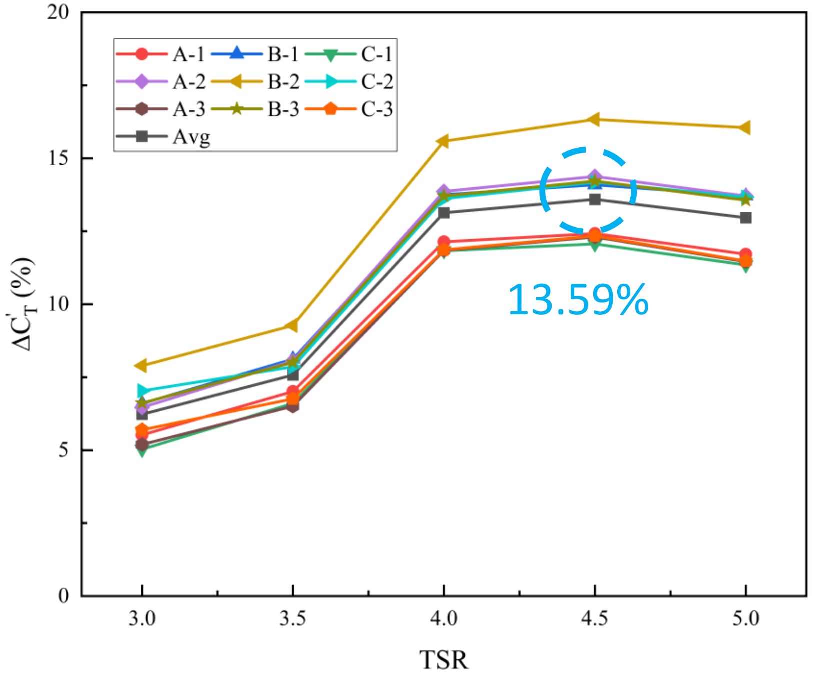
Running at the optimal TSR for single rotor case (TSR=4) might not be optimal for the MRDAWT system.



Variation of ΔC_P under different TSR



Variation of ΔC_T under different TSR



Variation of $\Delta C_T'$ under different TSR

Conclusion

- The performance of AL-PyFR(DAWT) model in MRDAWTs system prediction is validated by comparing with LES-AL model, LBM-AL model and experiment results of a 5-rotor system .
- The AL-PyFR(DAWT) model successfully captured ΔC_P due to blockage effect and the asymmetric ΔC_P distribution linked to wake interaction and unidirectional rotation.
- In the 9-rotor system, the gap spacing sensitivity analysis revealed that the maximum average system efficiency occurred at S = 0.3.
- In the TSR sensitivity analysis, optimal system performance was achieved at TSR = 4.5 for both ΔC_P and ΔC_T.
- These results demonstrate that MRDAWTs system performance is highly dependent on rotor layout and operating conditions, providing valuable insights for system optimization.

Future Work

- Develop a generalized diffuser force projection framework using machine learning or adaptive algorithms, eliminating the need for manual adjustment.
- Propose a tip-loss correction model specifically for DAWTs, improving accuracy in blade-tip flow predictions.
- Extend the model to include floating platform motions by coupling with structural solvers, enabling realistic offshore simulations.
- Integrate with optimization algorithms to co-optimize rotor layout and operating parameters, balancing efficiency and structural loading.

Thank you.

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