Power Optimization of Wind Turbines Affected by Wake

Yousef Akhavan

York University

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Wind farm power optimization

Currently, wind turbines are operating at their own local optimum points to maximize their own performance. This leads to the suboptimal performance of the overall wind farm.

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- Deterministic assumption for the incoming wind speed.

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Outline:

1. Motivation

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2. Literature Review

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3. Wind Farm Power Optimization Model

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5. Numerical Results

Motivation

- Increasing the power capture efficiency of existing wind farms.

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- Reducing the loads on the blades.

literature review

- Modeling of a free-standing wind turbine

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  - Torres et al. in 2011 studied power optimization with improved BEM method.

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- We develop a model for wind farm power optimization:
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  - Based on actuator line model combined with Navier-Stokes equations.
- We develop an efficient numerical algorithm.
- We increase the total power by 9%.

Wind farm power optimization model

$$\underset{\substack{\beta_1,\ldots,\beta_N \\ \Omega_1,\ldots,\Omega_N}}{\text{Max}} \quad \sum_{i=1}^{N} P_i$$

subject to $\beta_{\min} \leq \beta_i \leq \beta_{\max}, \quad \Omega_{\min} \leq \Omega_i \leq \Omega_{\max}$ and

Wind farm power optimization model

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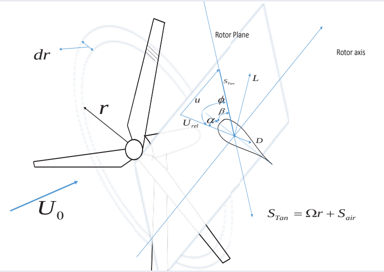
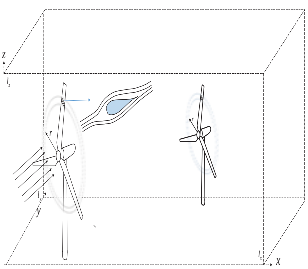
$$\frac{\partial \omega}{\partial t} + \mathbf{U}.\nabla\omega = \omega.\nabla\mathbf{U} + \frac{1}{Re}\nabla^2\omega + \nabla \times \mathbf{f}_\epsilon.$$

$$\omega = \nabla \times \mathbf{U},$$

$$\nabla \cdot \mathbf{U} = 0.$$

Objective function evaluation





$$P_i = \frac{\rho B \Omega}{2} \int_0^R \Big(U_{rel}^2(r) c(r) b(r) \Big(C_L(\alpha(r)) \sin(\phi(r)) - C_D(\alpha(r)) \cos(\phi(r)) \Big) \Big) r dr,$$

$$dT_i(r) = (L(r)\cos(\alpha(r) + \beta(r)) + D(r)\sin(\alpha(r) + \beta(r)))Bdr,$$
$$d\Psi_i(r) = (L(r)\sin(\alpha(r) + \beta(r)) - D(r)\cos(\alpha(r) + \beta(r)))Bdr.$$

Proposed numerical algorithm

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  - Solve Navier-Stokes equations where the external forces are determined by the actuator line method.

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- Initial operating points, $\beta_i, \Omega_i, i = 1, \cdots, N$.
- Choose search directions at each iterate.
- Evaluate the total power:
  - Solve Navier-Stokes equations where the external forces are determined by the actuator line method.
- Select the operating points with a higher total power.

Model Validation by Experimental Data

Figure 1: WindSpot

- 3.5 kW three-bladed wind turbine.

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- the chord length is 0.25m at the hub and 0.15m at the tip.

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Figure 1: WindSpot

- 3.5 kW three-bladed wind turbine.
- with a rotor diameter of 4.05 meters.
- the chord length is 0.25m at the hub and 0.15m at the tip.
- operating at $\Omega = 12\frac{rad}{s}$ and $\beta = 10.5$.

Numerical Results

Model Validation by Experimental Data

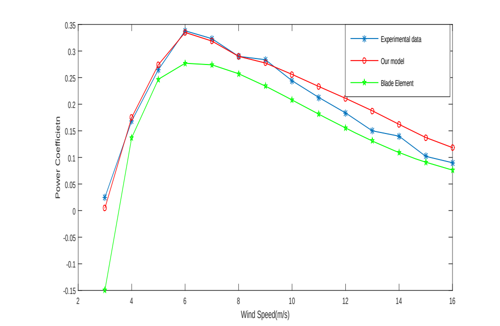

Figure 2: Comparison of measured and computed power.

Wake Structures

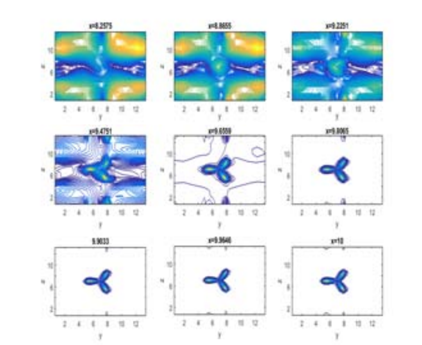

Figure 3: Computed magnitude of vorticity at y-z planes for $U_0 = 10\frac{m}{s}$.

Wake Structures

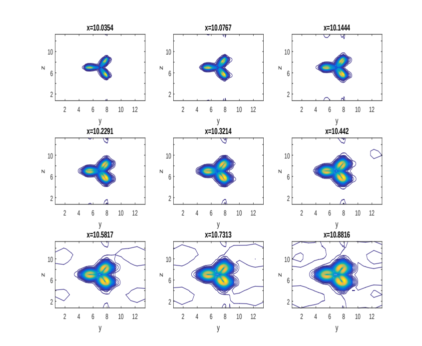

Figure 4: Computed magnitude of vorticity immediately behind wind turbine.

Wake Structures

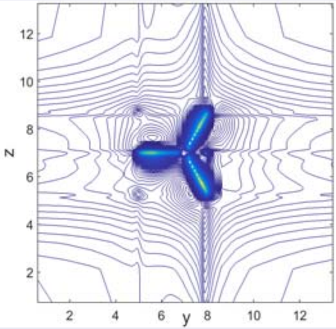

Figure 5: Distribution of axial factor (1-U/U0) in the rotor plane for $U_0 = 10$.

Wake Structures

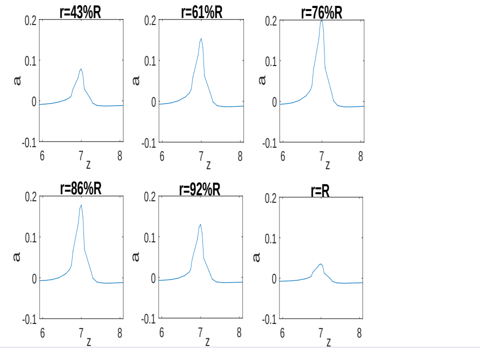

Figure 6: Distribution of axial factor in z direction.

Wake Structures

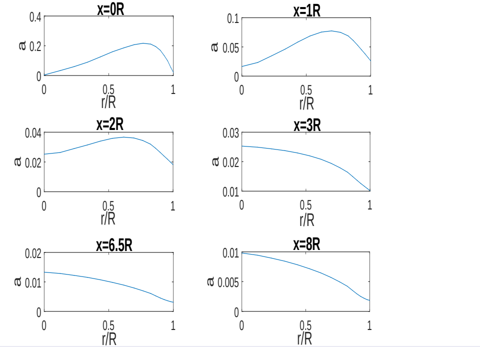

Figure 7: Distribution of axial factor along the blade (wake region).

Wake Structures

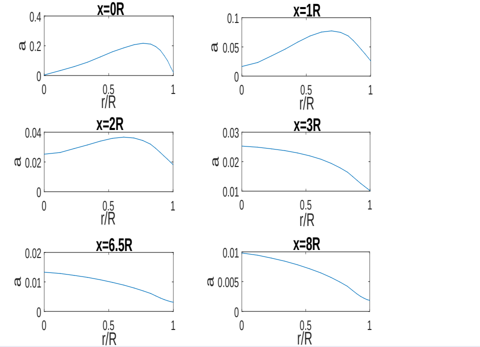

Figure 8: Distribution of axial factor along the blade (wake region).

Optimization Results

Table 1: Optimal operating point of NACA 23012.

Wind speed	init.	β	Ω	α	T	Ψ	P
U_0=9 $\frac{m}{s}$	(-3, 2)	1.121	1.68	13.046	5.687	0.807	20.511
U_0=10 $\frac{m}{s}$	(1, 1.9)	1.375	1.800	13.187	6.545	1.010	30.006
U_0=11 $\frac{m}{s}$	(2, 1)	1.414	2.050	13.419	8.090	1.241	40.544

Optimization Results

Table 2: Optimal operating point of NACA 23012 (different initial point).

Wind speed	init.	β	Ω	α	T	Ψ	P
$U_0{=}9\ \frac{m}{s}$	(0, 1)	1.121	1.683	13.046	5.687	0.807	20.511
$U_0{=}10\ \frac{m}{s}$	(-2, 1)	1.375	1.802	13.188	6.545	1.010	30.006
$U_0{=}11\ \frac{m}{s}$	(-2, 1.7)	1.416	2.055	13.412	8.090	1.240	40.543

Optimization Results

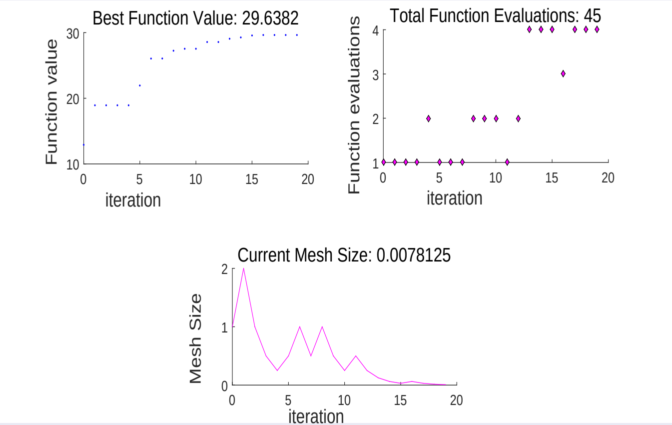

Figure 9: Pattern search result for the incoming wind speed $U_0 = 10$.

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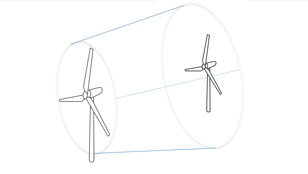

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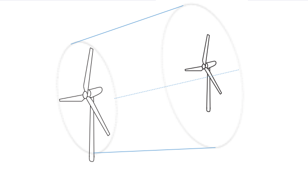
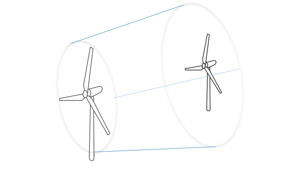


Table 3: Joint optimal operating points of two NACA 23012.

Wind speed		β	Ω	α	T	Ψ	P
$U_0{=}9\ \frac{m}{s}$	1st	1.12	1.68	11.30	5.14	0.643	16.49
	2nd	1.12	1.68	11.16	5.11	0.629	16.22

Optimization Results



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$U_0{=}9\ \frac{m}{s}$	1st	1.12	1.68	11.30	5.14	0.643	16.49
	2nd	1.12	1.68	11.16	5.11	0.629	16.22
	1st,	1.16	1.59	13.12	5.17	0.755	18.57
	2nd,	0.74	1.30	22.36	5.22	0.750	17.10
					Gain:	9.04%	

Thank you!