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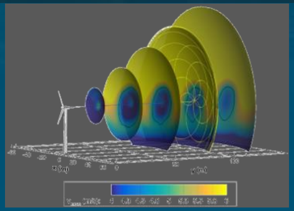
Towards Periodic Blade Pitching to Increase Deep Array Power in Wind Plants



PRESENTED BY

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Wind Energy Technologies / Thermal-Fluid Science & Engineering

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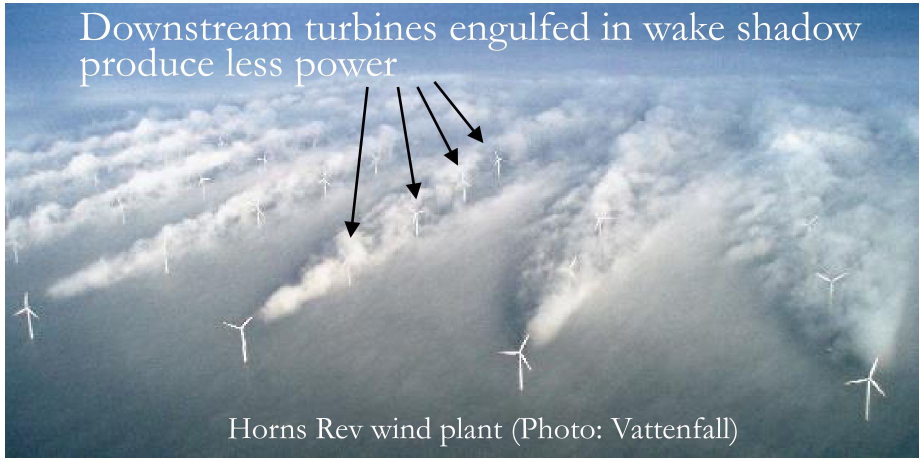
Introduction

Overview of wake recovery

- Deep array losses have been observed larger than 40% for stable ABLs [1,2].
- The near wake is shielded from the mean-flow kinetic energy of the ambient flow by the helical tip vortices [3].
- Induction control and wake steering have shown promise to help with array losses, but speeding the transition to the far wake via the breakdown of the tip vortices may be fundamentally more appealing.



Horns Rev wind plant (Photo: Vattenfall)

Inherent wake instabilities

Intentional wake forcing in open literature

Introduction

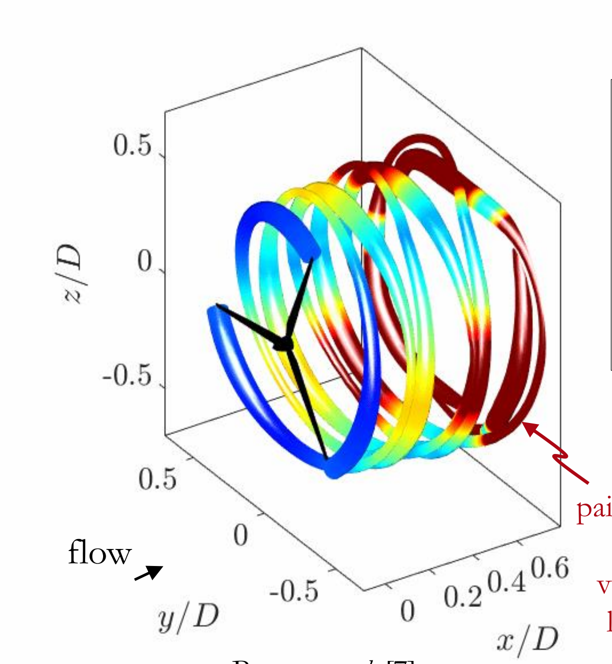
Overview of wake recovery

Inherent wake instabilities

- Experiments have validated that the streamwise distance before vortex breakdown is inversely proportional to turbulence intensity [4-6]
- Why?...Initial perturbations excite wake instabilities:
  - Tip vortex – frequency scaling on RPM
  - Hub vortex – frequency scaling not unanimous
  - Bluff body – frequency scaling on U_∞/D

Intentional wake forcing in open literature

Tip vortex (i.e., mutual inductance) instability:



Brown *et al.* [7]

Perturbation wavenumbers:

$\omega = N_b(k - 0.5)$ cycles/rev.

number of blades

frequency parameter (k = 1 mode is most amplified)

Red indicates successful vortex pairing and imminent "leapfrogging" (i.e., 90° rotation of adjacent vortices around saddle point) that leads to helical wake breakdown

Exciting the tip vortex instability is one proposed approach to improving wake recovery

Introduction

Overview of wake recovery

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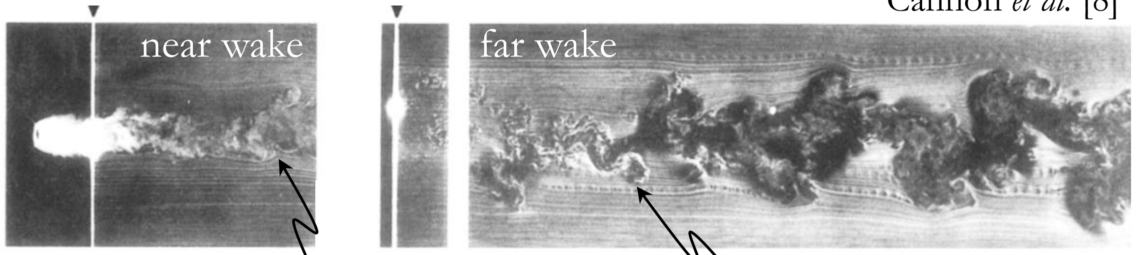
  - Hub vortex – frequency scaling not unanimous
  - Bluff body – frequency scaling on U_∞/D

Intentional wake forcing in open literature

Bluff body instabilities:

Flow normal to disk:

Cannon *et al.* [8]



Initial perturbations

Coherent structures with $St_D \approx 0.15$ help to entrain ambient fluid

Flow normal to wind turbine:

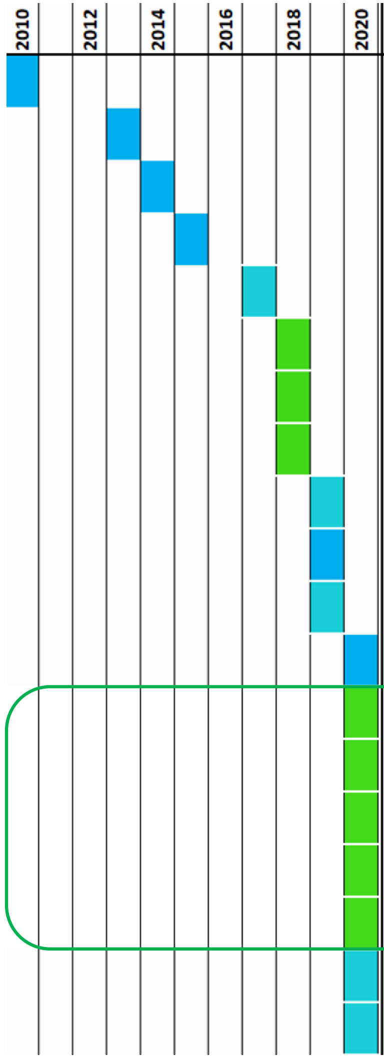
- "[There is] vortex shedding from the turbine disc, much in the same way as one would expect for a solid disc." -Medici and Alfredsson [9]
- Recent authors have found preferred excitation frequencies found in the St_D range of 0.2-0.5 [10-15]
  - Preferred frequencies are lower than those of the tip vortex instability (roughly an order of magnitude lower for the configuration of this study)

Exciting bluff body instabilities is another approach to improving wake recovery and the one we leverage here…

Introduction

Targeted instability
- Bluff body instability
- Tip vortex instability
- Hybrid/ambiguous

Intentional wake forcing in open literature*



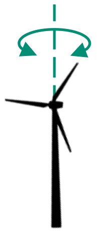
Authors	Institution(s)	Method	TI	Perturbations	Parameters	Benefit
Ivanell et al	KTH, DTU	ALM	0?	sinusoidal force near tip	f, A	~40% reduction in near wake length
Odemark et al	KTH Mechanics	Wind tunnel	0.05%	sinusoidal force near tip	f, A	tip vortex energy reduced to 0 by x/R = 1.4
Sarmast et al	KTH, DTU, Uppsala	ALM	0?	sinusoidal/uniform force near tip	f, A	double the spatial growth rate?
Quaranta et al	Aix-Marseille University, Airbus Helicopters	Flume	<1%	sinusoidal variation in rotation rate	f, A	60% reduction in distance to first pairing
Castillo et al	TTU	Wind tunnel	0.12%	sinusoidal variation in rotation rate	one test	smaller velocity deficit
Munters et al	KU Leuven	ADM	?	sinusoidal Ct & yaw angle, spacing, alignment	f, A	up to 66% gain in wind farm efficiency
Munters et al	KU Leuven	ADM	?	sinusoidal variation in Ct, first row	f, A	for 12x6 farm, 0.5% power increase
Yilmaz et al	KU Leuven	ALM	1,5,10%	torque and pitch derived from optimization, TI	prescribed signal	up to 15% power increase for two turbines
Kimura et al	University of Tokyo, JAXA	ADM?	?	yaw angle	f, A	60% increase in REWS at 5D
Kleusberg et al	KTH, Ecole Normale Superieure Paris-Saclay	ALM	0?	sinusoidal force near tip	f, A	
Houck et al	Cornell University	Flume	3.90%	step change in rotation rate, duty cycle	f, A	greater vortex decay, turbulence, and wake width growth
Marten et al	TU Berlin, TWTH Aachen	LLVFW/ALM	10%	flaps	f, A	~60% reduction in near wake length
Frederik et al	TU Delft	ALM	5.90%	sinusoidal IPC, yaw angle, tilt angle	f, A	12.4% increase in energy at 7D
Wang et al	TU Munchen, Fraunhofer IWES	ALM/wind tunnel	5%	sinusoidal pitch	f, A	3.6% increase in three turbine power
Frederik et al	TU Delft	ALM	0,5%	sinusoidal IPC, TI	f, A	up to 7.5% increase in two turbine power
Cacciola et al	Politecnico de Milano	ALM	?	sinusoidal pitch	f, A	up to 20% gain in two turbine power
Frederik et al	TU Delft	ALM/wind tunnel	~5,~14%	sinusoidal pitch	f, A	up to 4% increase in three turbine power
Abraham et al	University of Minnesota, NREL	ALM	0	sawtooth pitch, sinusoidal yaw, TI	f, A	
Abraham et al	University of Minnesota, NREL	ALM	0	sawtooth pitch, sinusoidal yaw	f, A	

Our study uses a similar forcing strategy as these

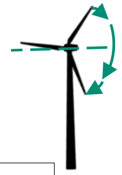
*IP for this technology held by Vestas – US patent: 10677221; Global patent: EP 2758660 A1

Active Wake Mixing Strategies

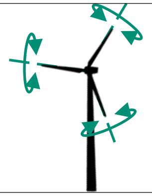
Control vectors:



Periodic yawing: typical yaw rates of large turbines (0.3°/s for the NREL 5MW [29]) are likely **too slow** to achieve meaningful oscillation amplitude needed to gain active control authority



Periodic rotor speed: generator speed control (almost instantaneous response) provides sufficient response to gain active control authority



Periodic pitching: blade pitch rates (8°/s for the NREL 5MW [29])) provide sufficient response to gain active control authority

Our analysis considers a periodic pitching control strategy for an upwind turbine*:

- Pitch control: $\beta = \beta_0 + A \sin(2\pi\, St\, U_{hub}\, D^{-1}\, t + \phi)$

  dynamic pitch setting (β); *conventional pitch Region 2.5 set point* (β_0); *amplitude* (A); *Strouhal number* (St); *phase* (ϕ)

  where…

  $\beta_0 = 0°$

  $A = 0°$, ~~1°~~, $2°, 3°$

  $St = 0.3$

  $\phi = 0°$

- Torque control: low-pass filter applied to rotor speed before signal goes to torque controller

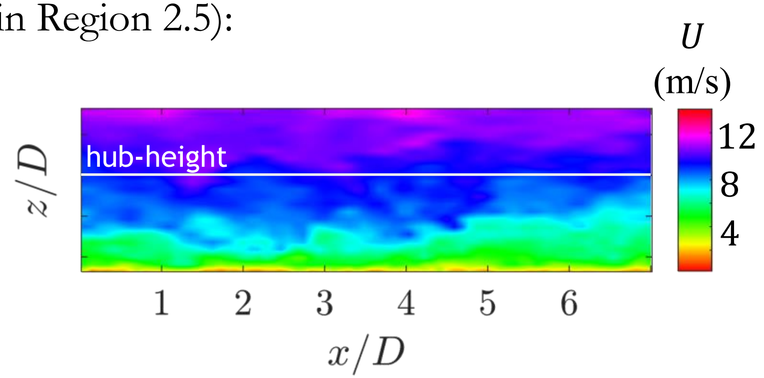
* Downwind turbine uses the default controller

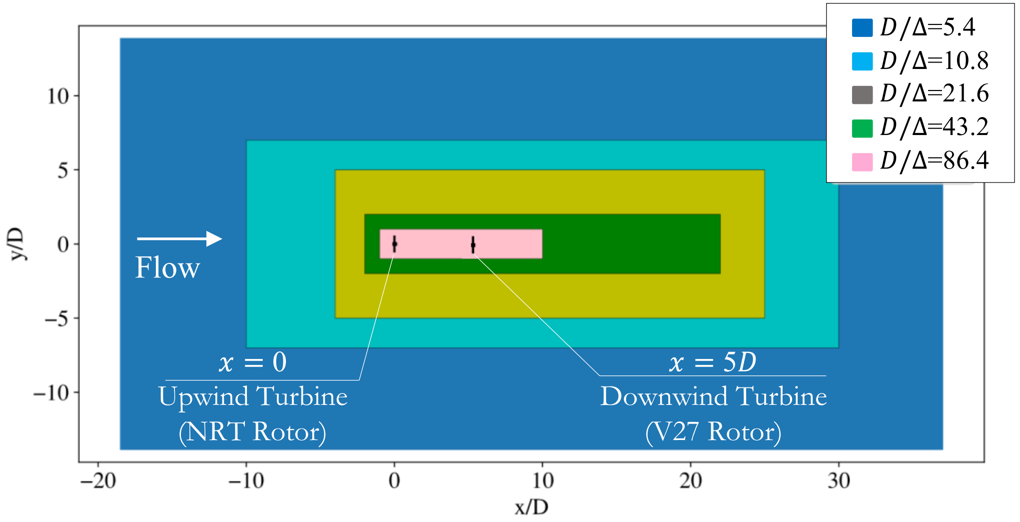
Computational Approach

This work employs large eddy simulations (LES) with actuator line formulation, which has accurately modeled bluff-body wake instabilities in previous analyses of turbine wakes

- Simulations use the multi-physics, massively parallel LES code Nalu-Wind, part of the ExaWind code suite [30], which has a pedigree of wake analysis studies [31-32]
  - One-equation, constant coefficient, turbulent kinetic energy (TKE) model
  - Actuator line model (ε =0.625)
  - Simulation time: 564 s (i.e., >200 independent flow realizations based on wake integral timescale)
  - Coupled dynamic response of the wind turbines is performed through the OpenFAST software suite [33]
- Inflow (stable ABL in Region 2.5):

U_{hub} = 9.21 m/s
TI_{hub} = 5.62%
α = 0.400
veer = 3.51°



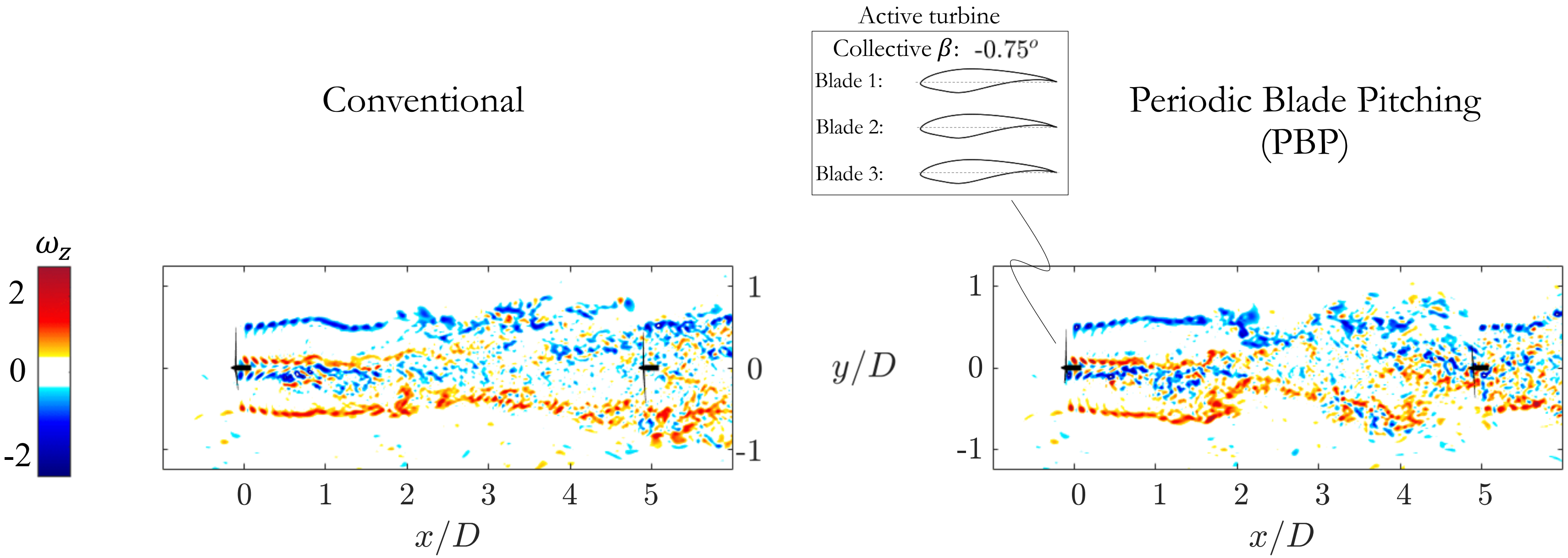


- Domain layout replicates the configuration at the DOE/SNL SWiFT facility; two inline turbines ($D = 27\ m, H_{hub} = 32.1\ m$) separated by $5D$
  - Upwind: National Rotor Testbed (NRT) rotor*
  - Downwind: Vestas V27 rotor
    - Modal analysis of the V27 turbine indicates that the lowest resonant frequency is 0.99 Hz, which is 10 times faster than the forcing frequency to be applied
    - Modal analysis results have not yet been performed on NRT rotor but are expected to follow similarly to the V27 results

*NRT rotor maintains kinematic similarity and loose dynamic similarity with GE 1.5sle [34]

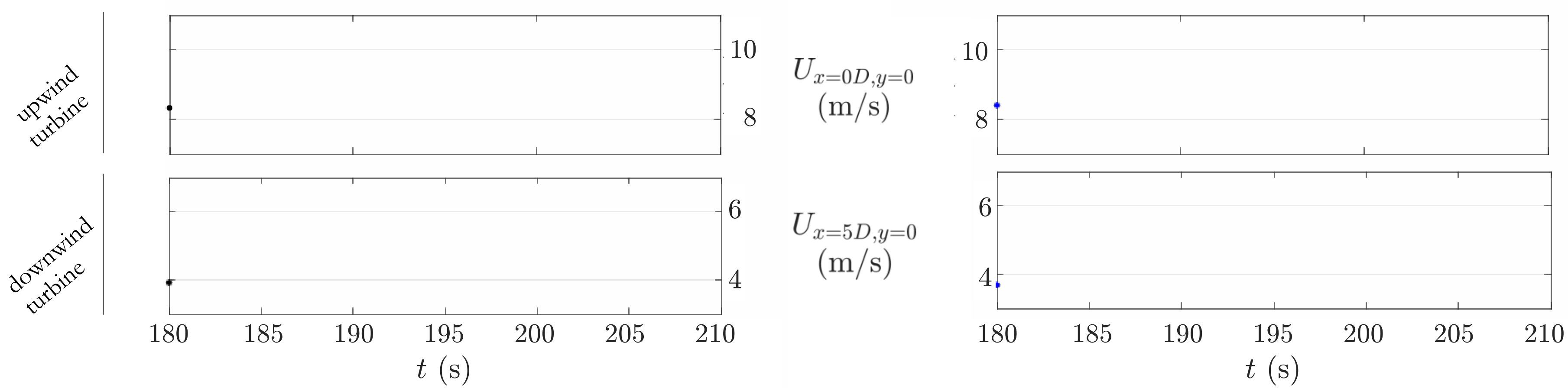
Results - Flowfield QoIs (Pitching amplitude, $A = 3°$)

Hub-height vorticity:



PBP amplifies coherent structures that generate mixing across the shear layers

Hub-height velocity:

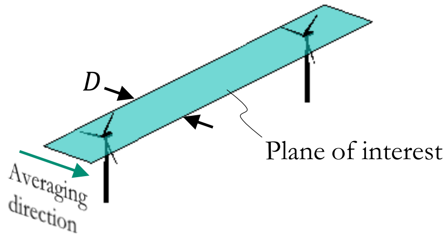


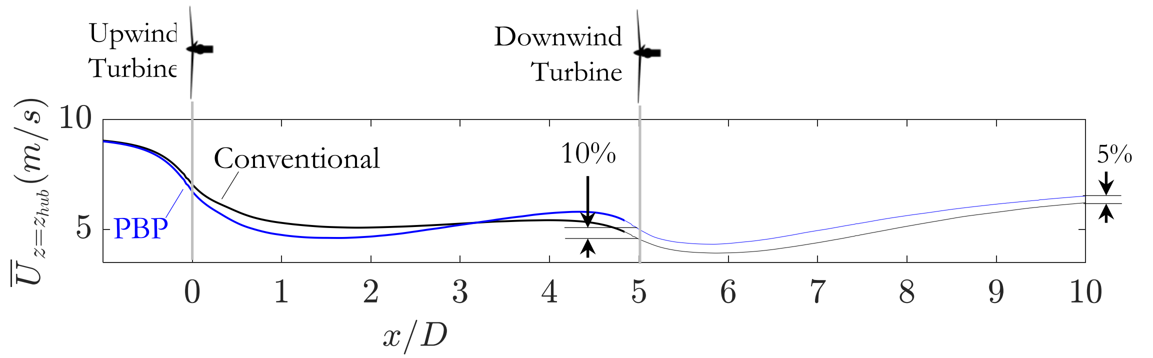
Inflow velocity of upwind turbine is minimally affected by PBP

Inflow velocity of downwind turbine gets ~10% boost from PBP

Results - Flowfield QoIs (Pitching amplitude, $A = 3°$)

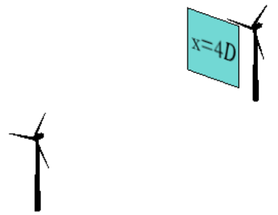
Mean hub-height velocity:
(averaged over y and t):

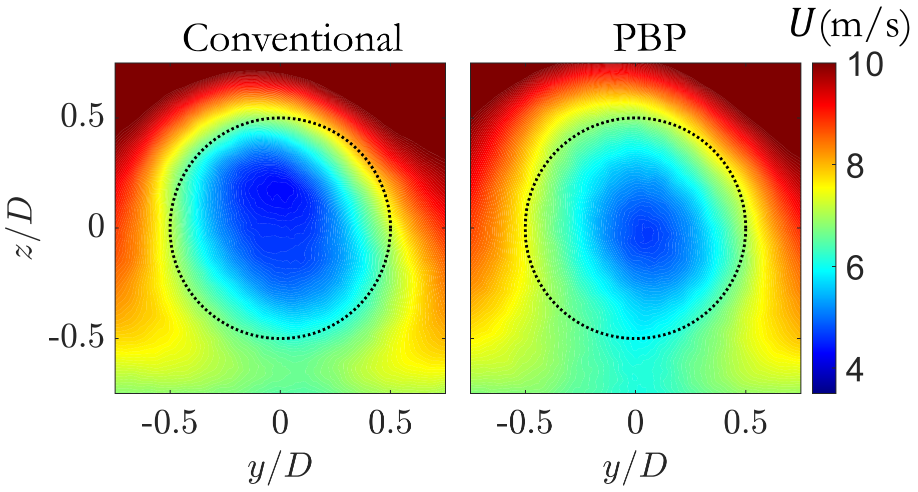


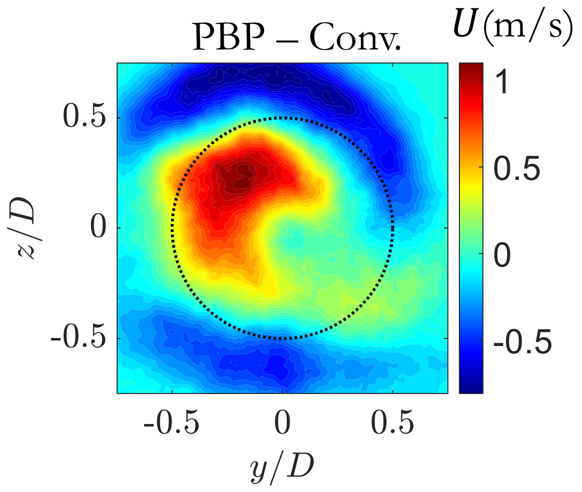


A hypothetical third turbine would also benefit from the first turbine's active mixing

Mean hub-height velocity:
(averaged over t):







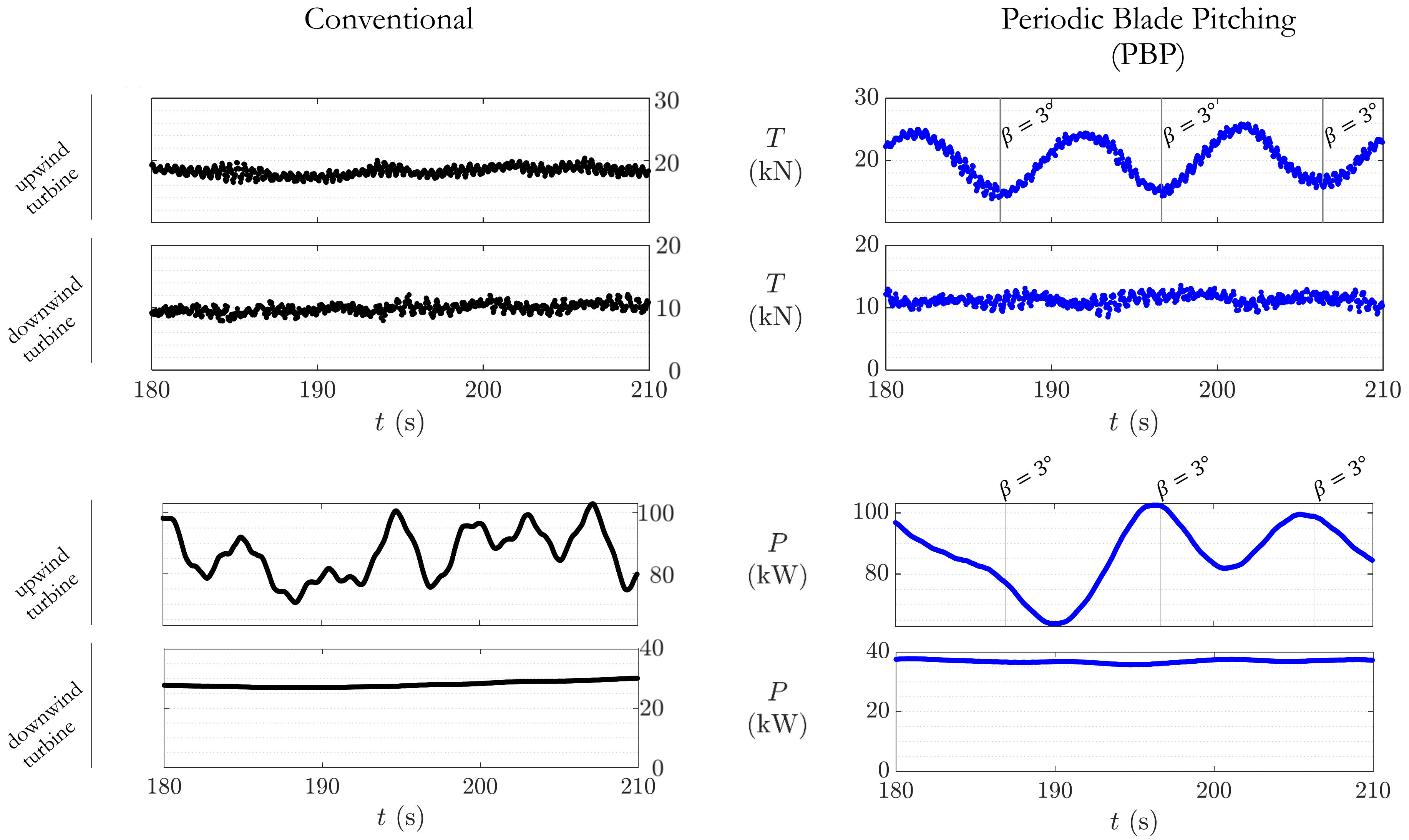
Largest velocity gain is near top of azimuth at ~75% span

Velocity is lower outside the rotor swept area (i.e., PBP is depositing mean-flow kinetic energy from the ambient flow into wake)

Results - Turbine QoIs (Pitching amplitude, A = 3°)

Thrust:

Power:



Cyclic loading from PBP ≫ cyclic loading from shear/veer

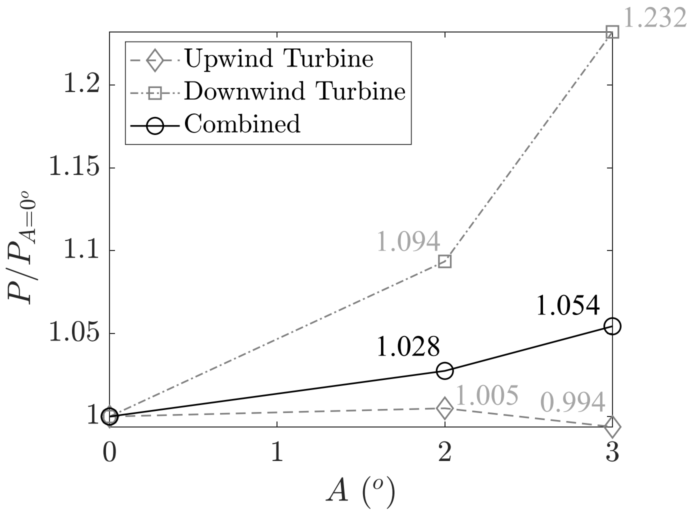
Downwind turbine loading not strongly influenced by PBP

Upwind turbine power lags thrust (by ~140° over full time series)

Downwind turbine shows >20% increase in power with PBP

Results - Turbine QoIs (Pitching amplitude, $A = 2°, 3°$)

Normalized Power:

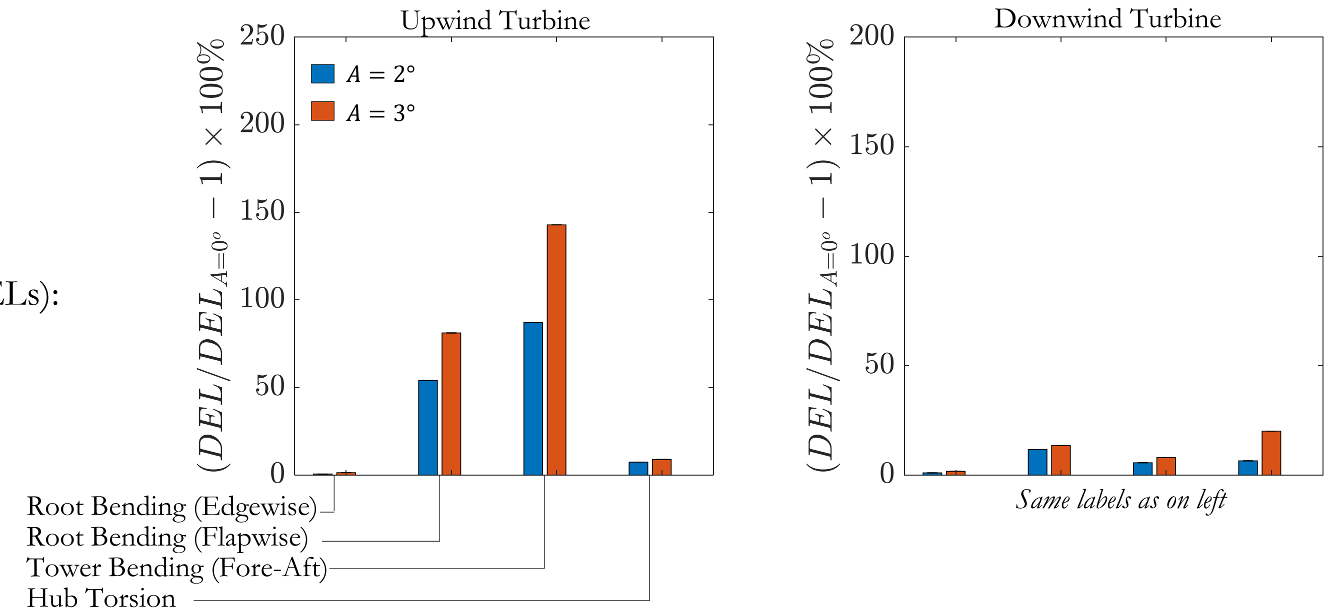


~23% increased power predicted for the second turbine at the highest pitch rate with likely increases of 10-15% power possible for a third turbine

Active turbine may experience drop in power (<1%) as it makes periodic excursions away from optimal axial induction

Two-turbine power gain of up to 5.4%

Normalized Damage Equivalent Loads (DELs):



The fatigue penalties associated with PBP on the upwind turbine components follow the same ordering as in Wang *et al.* [13] and Frederik *et al.* [14]…

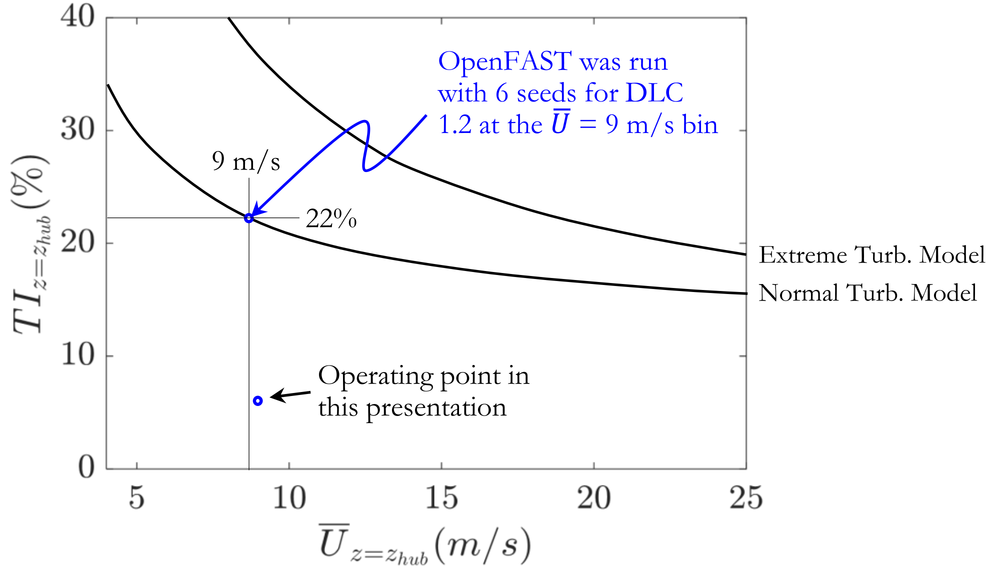
- Tower base
- Blade root (flapwise)
- Shaft

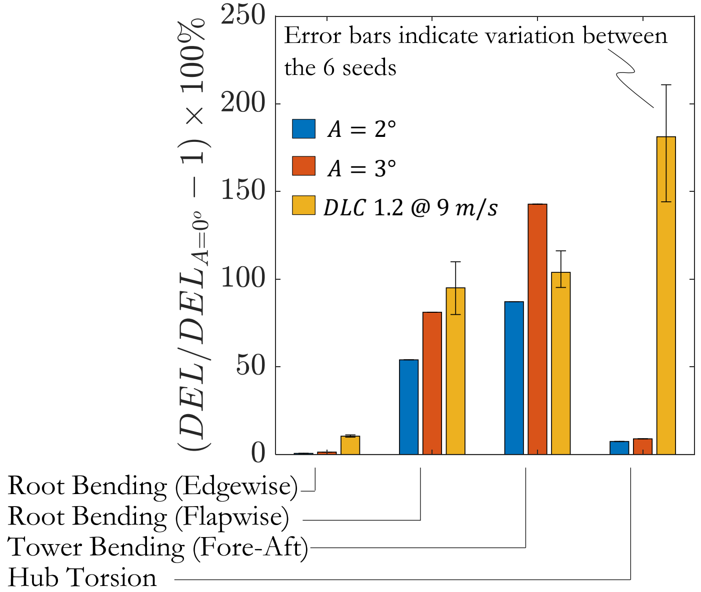
decreasing DEL penalty

The downwind turbine sees only modest fatigue increases; no more than 25% increase for any of the four DELs considered

Discussion

How do PBP fatigue loads in a stable boundary layer compare to NTM fatigue loads from DLC 1.2?





Only in one case (i.e., fore-aft tower root bending) is the damage from PBP in the stable ABL worse than the damage from the DLC 1.2 runs at a similar mean inflow velocity

- For the fore-aft tower root bending, PBP results in an increase in 26-46% in tower root bending moment DEL, which equates to a 50-68% reduction in life assuming m = 3 for the steel base

However, fatigue is not the design driver for the NRT/V27 rotors (nor is it for many large diameter utility scale turbines)

- Open questions: (1) does PBP make fatigue the design driver and/or (2) how does PBP affect tower clearance and ultimate loads?

Summary and Conclusions

Active wake mixing with Strouhal-scaled excitation frequency has been demonstrated with actuator-line LES for research-scale turbines using PBP

PBP increased the inflow velocity to the second turbine by as much as 10%, and gains for the third turbine in the row are also implied

The high-fidelity model predicted a 23% increase in power for a downstream turbine at $5D$ spacing using the largest pitching amplitude studied of $3°$ (5.4% gain for the combined two turbine system)

The tower base is the only turbine component studied that receives more damage from the PBP strategy than from DLC 1.2 at similar mean inflow conditions; the base would see a 50-68% reduction in life if PBP were activated continuously at the largest pitching amplitude

Future Work?

More fully characterize the potential of periodic wake forcing with…

- Other control vectors that produce no direct mechanical wear (i.e., rotor speed control)
- Inflow conditions with higher turbulence

Explore potential for power increase in deeper arrays of turbine

- How many turbine rows downstream in an array benefit from actuating the front-row turbine?
- Is there a benefit to actuating some or all the downstream rows of turbines in the array at a lower amplitude?

Perform full turbine system lifetime reliability analysis to optimize the activation of the control scheme considering the tradeoff between increased power and loads

- Does PBP affect the critical design load cases?
- Quantify real-time power value versus the long-term cost of decreased blade life
- Calculate potential LCOE reduction considering time-varying wind resource

Thank you!

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