Comparing feedforward individual pitch control performance of large floating offshore wind turbines

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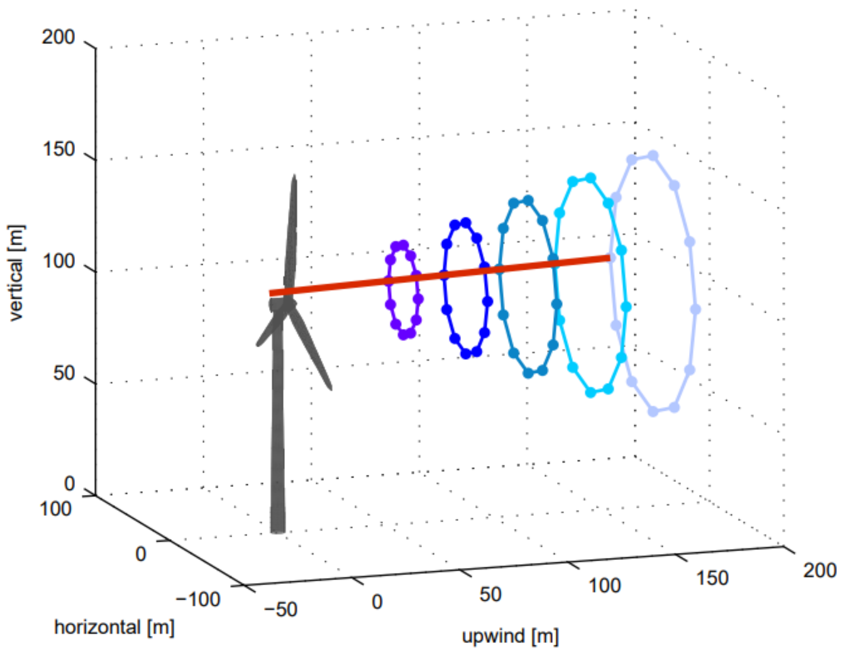
Introduction

Light Detection and Ranging (LIDAR)

- Wind velocity measurement device that operates by firing high speed laser pulses, which are reflected by particulates in the air.
- Nacelle-mounted, forward-looking LIDAR can be used to measure the incoming wind to assist with wind turbine control.



Source: F. Dunne, D. Schlipf, L. Pao, A. Wright, B. Jonkman, N. Kelley, and E. Simley. Comparison of two independent LIDAR-based pitch control designs. In50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, page 1151, 2012.

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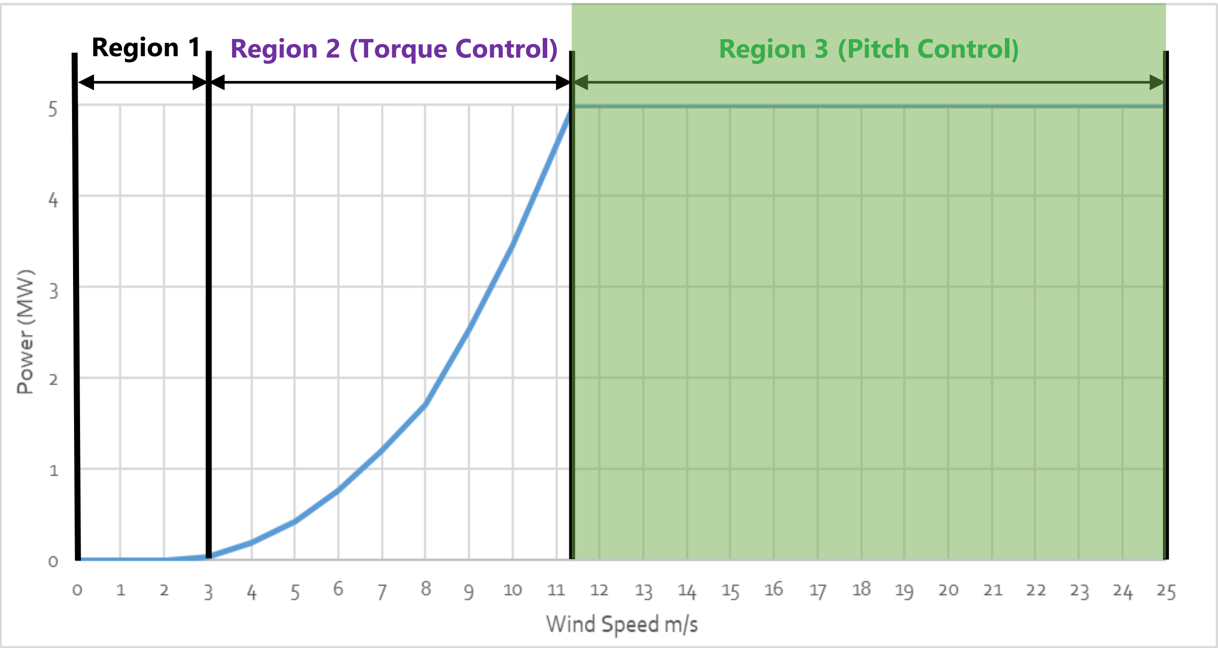
Introduction

LIDAR-assisted control benefits

- LIDAR-assisted control delivers its most significant benefits when assisting with pitch control in above-rated wind speed conditions.

- Benefits consist of superior rotor speed regulation and power tracking as well as loading and platform motion reductions



Source: J. Jonkman, S. Butterfield, W. Musial, G. Scott. Definition of a 5-MW reference wind turbine for offshore system development. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2009.

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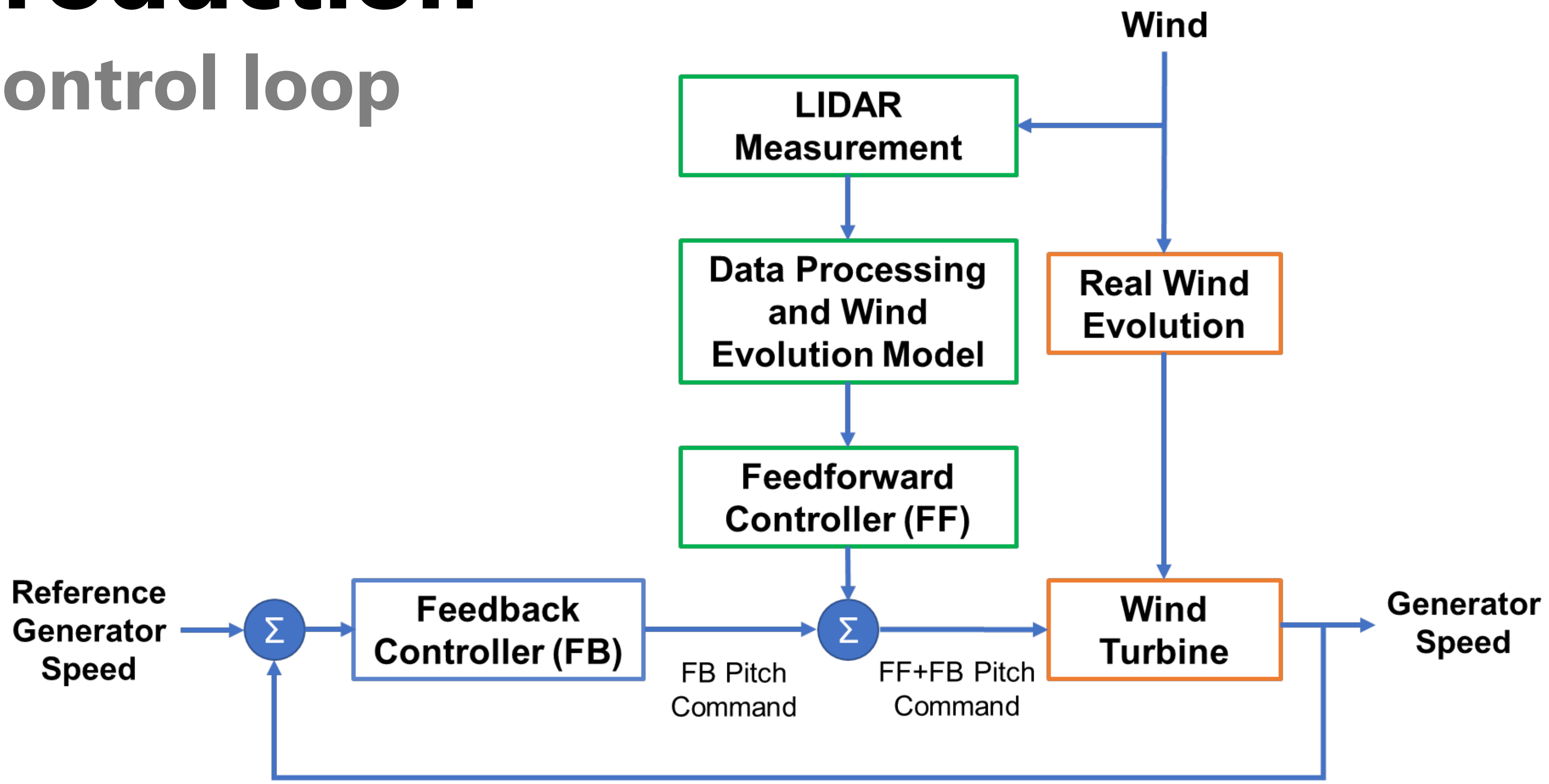
Introduction

FF control loop



Adapted from: A. Scholbrock, P. Fleming, D. Schlipf, A. Wright, K. Johnson, and N. Wang. LIDAR-enhanced wind turbine control: Past, present, and future. In 2016 American Control Conference (ACC), pages 1399–1406. IEEE, 2016.

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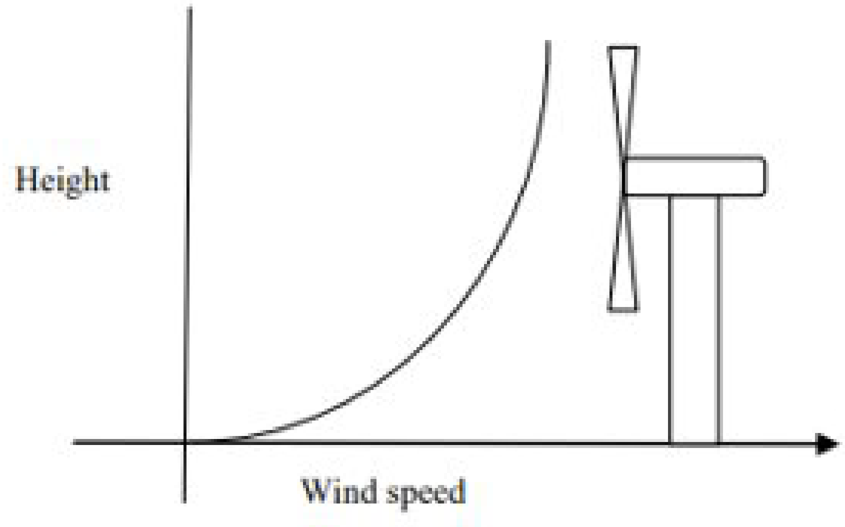
Introduction

Individual pitch control (IPC)

- Due to shear, veer and turbulence, wind speeds can vary greatly across the rotor swept area.
- Individual pitch control can be employed to overcome cyclic loads that occur due to these variations in wind speed across the rotor disk.
- This is especially relevant for turbines with large rotor diameters and swept areas.
- LIDAR can be used to deliver commands to individual blades for feedforward IPC



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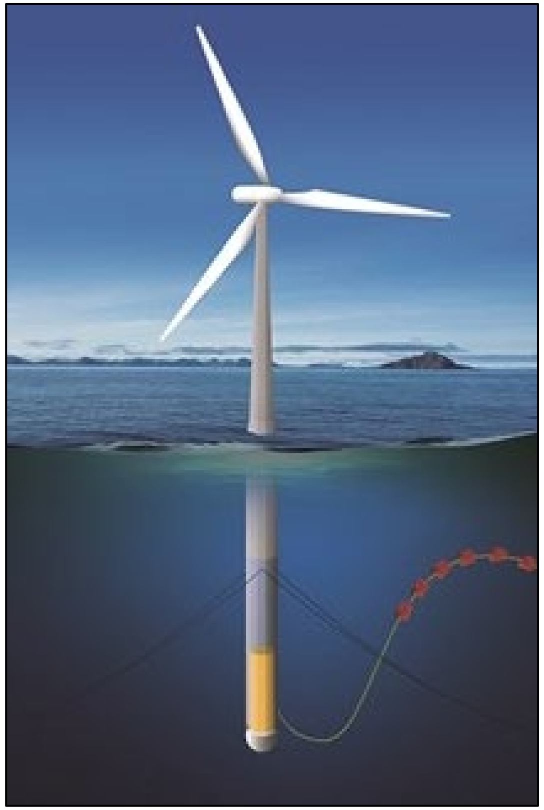
Turbine Substructure Models

IEA 15MW, UMaine VolturnUS-S & WindCrete Spar



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Turbine-substructure models

Floating turbine controller design

Coupling of platform motion and pitch control actuation results in negative damping

→

Pitch controller gains must be reduced to overcome negative damping

→

Degree of reduction depends on substructure. Low pitch controller gains = slow pitch actuation

→

Rate of pitch actuation affects feedforward control impacts

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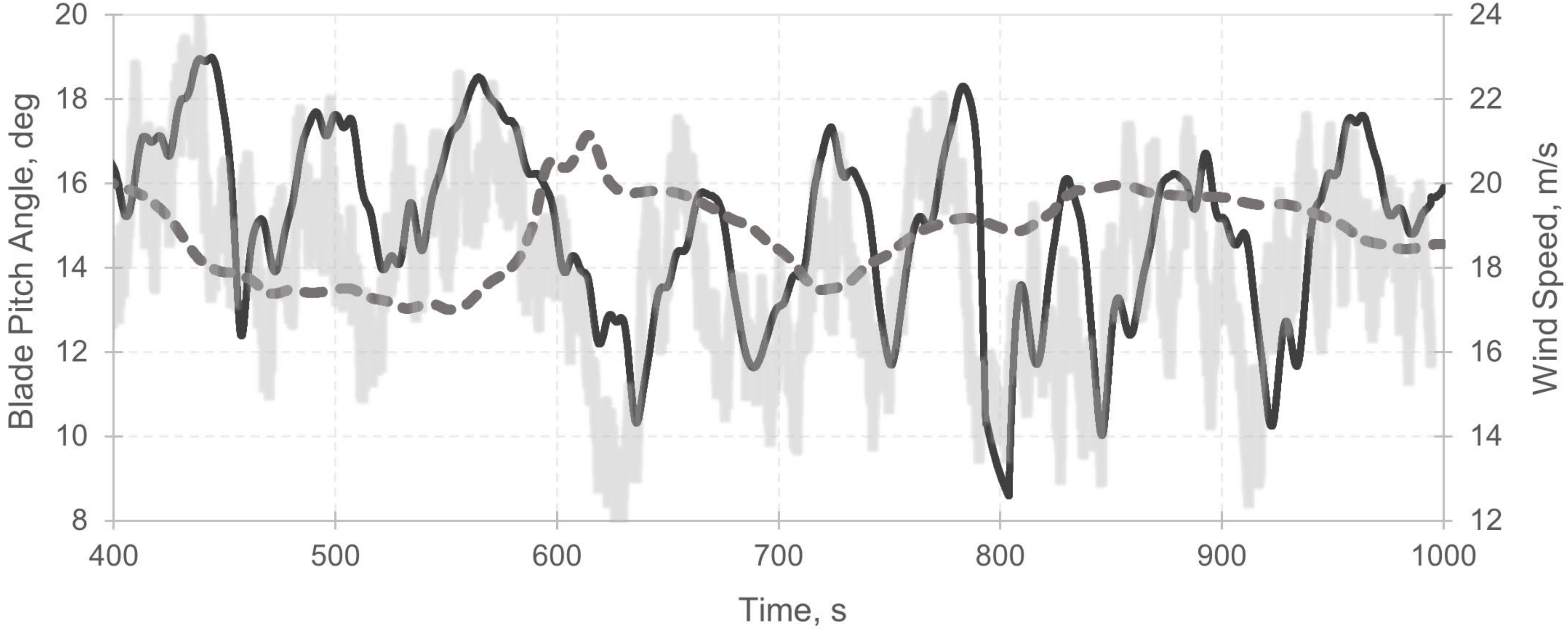
Turbine-substructure models

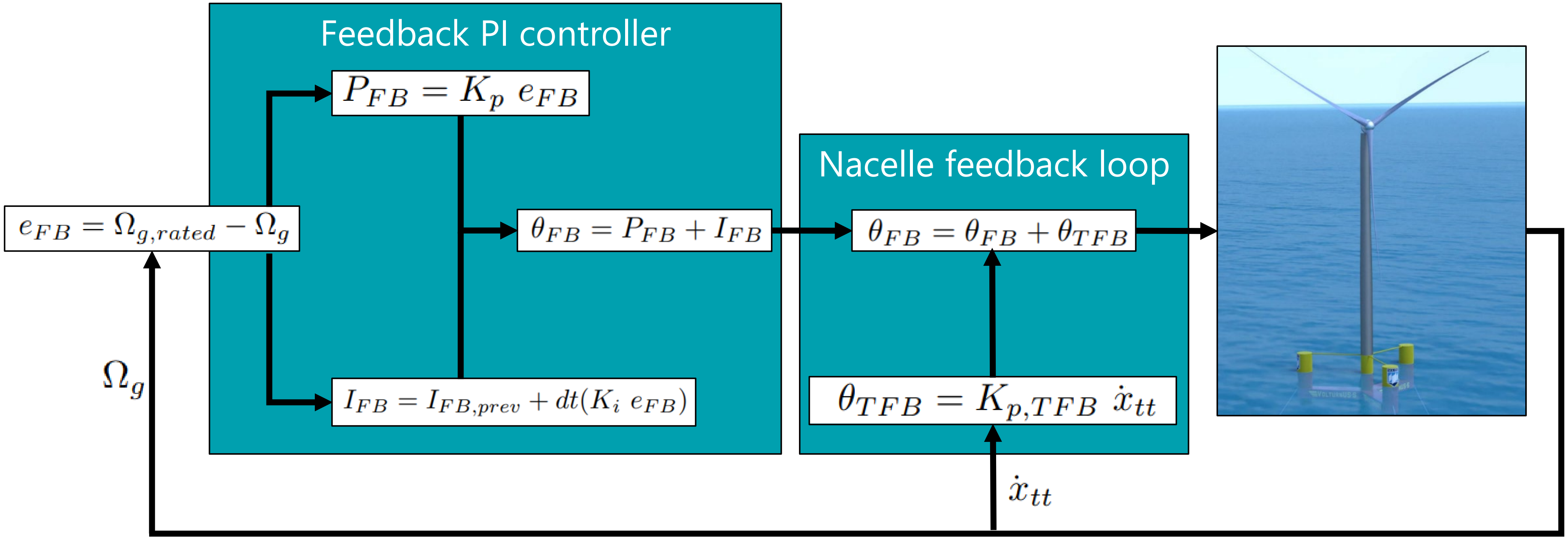
Blade pitch behaviour



Solid – Volturn Semi-Sub **Dashed** – WindCrete Spar Faded – Hub Height Wind Speed

Methodologies

Baseline feedback pitch controller (FB)



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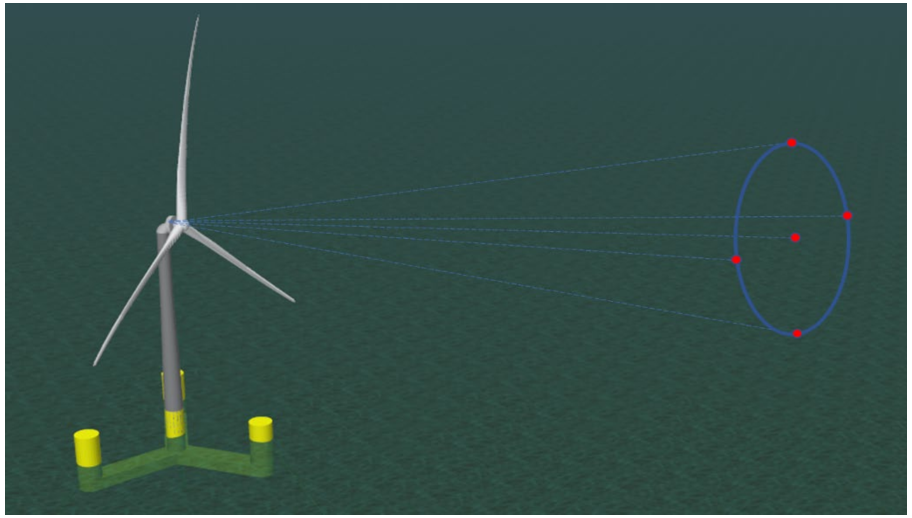
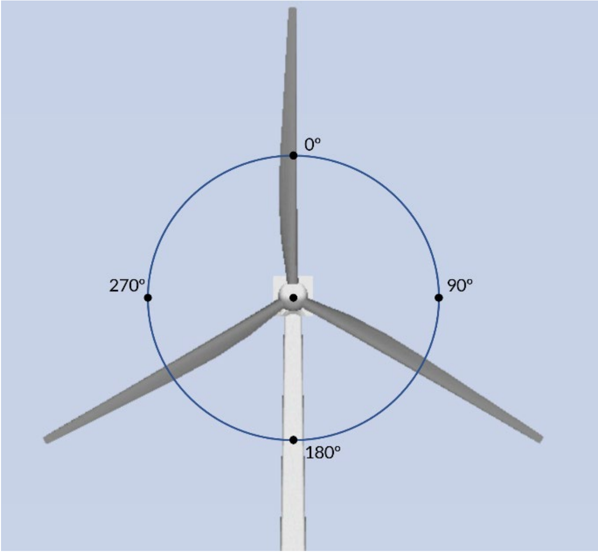
Methodologies

LIDAR simulator

- Study used OpenFAST InflowWind LIDAR simulator, available within OpenFAST v3.5 onwards.
- Simulator function, source code modifications, results and limitations were outlined in previous works[1].
- LIDAR simulator sits within InflowWind module. Measurements interfaced to ServoDyn and ROSCO to enable LIDAR-assisted control.
- Simulator uses 5 beams – One positioned directly ahead of the turbine and others positioned in 90° azimuth increments at 50% blade span.
- Configuration enabled feedforward collective and individual pitch control





[1] - Russell, A. J., Collu, M., McDonald, A. S., Thies, P. R., Keane, A., & Quayle, A. R. LIDAR-assisted feedforward individual pitch control of a 15 MW floating offshore wind turbine. Wind Energy. https://doi.org/10.1002/we.2891

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Methodologies

Feedforward collective pitch controller (FFCPC)

1. The feedforward command is calculated from the LIDAR measured REWS. Rate of change is calculated and used to modify the integral component of the feedback controller:

$$\dot{\theta}_{FF} = \frac{\theta_{FF} - \theta_{FF,prev}}{\Delta t}$$

$$I_{FF\text{-}FB} = I_{FF\text{-}FB,prev} + \Delta t \left(K_I \, e_{FB} + \dot{\theta}_{FF} \right)$$

2. The feedforward modified feedback command is issued:

$$\theta_{FF\text{-}FB} = \left(P_{FB} + I_{FF\text{-}FB} \right) + \theta_{TFB}$$

This methodology has previously been implemented in works by Schlipf et al.[1] and Guo et al.[2].

[1] Schlipf, D., Lemmer, F., and Raach, S.: Multi-variable feedforward control for floating wind turbines using LIDAR, in: The 30th International Ocean and Polar Engineering Conference, OnePetro, 2020

[2] Guo, F., Schlipf, D., and Cheng, P.: Evaluation of lidar-assisted wind turbine control under various turbulence characteristics, Wind Energy Sci., 8, 149–171, https://doi.org/10.5194/wes-8-149-2023, 2023.

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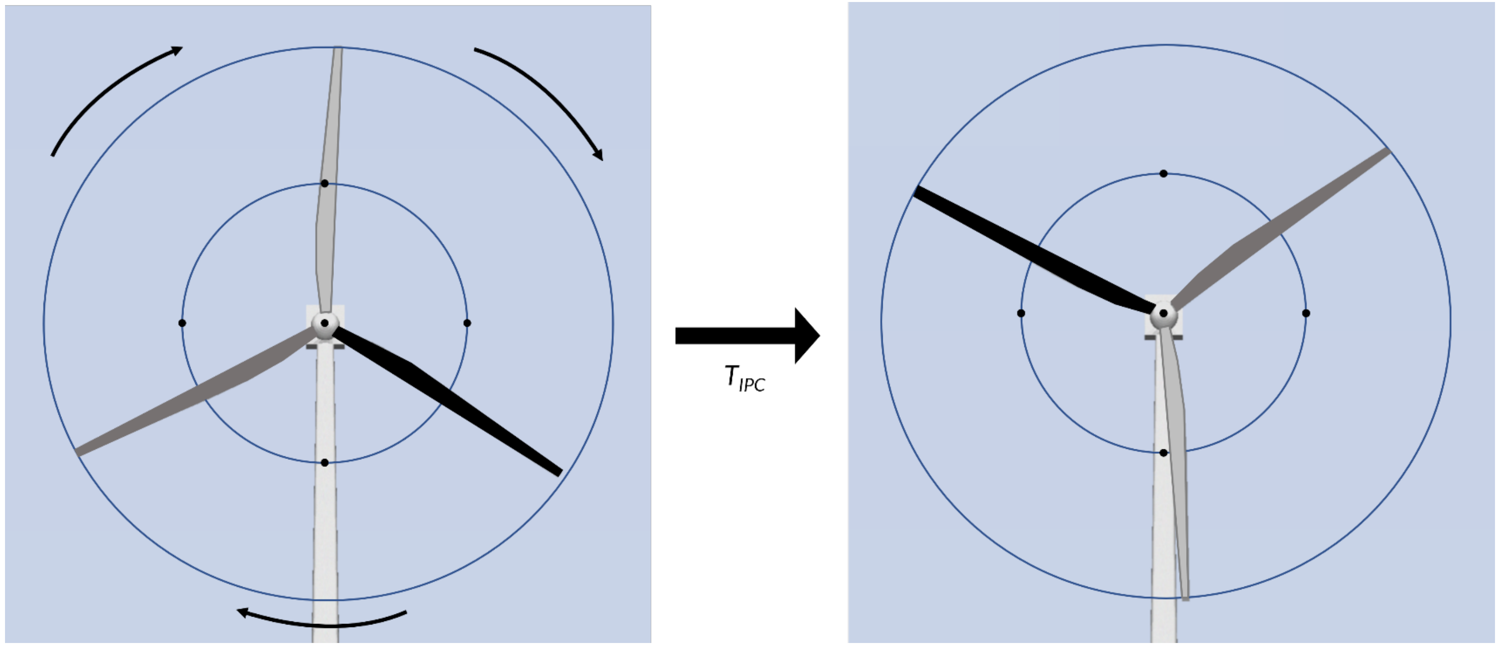
Methodologies

Feedforward individual pitch controller (FFIPC)[1]

1. The predicted azimuth angle of each blade after the time delay incurred by filtering of the individual pitch commands (T_{IPC}) is then determined from the current rotor rotational speed, Ω_r.

$$A_{k,new} = A_k + \Omega_r \, T_{IPC}$$



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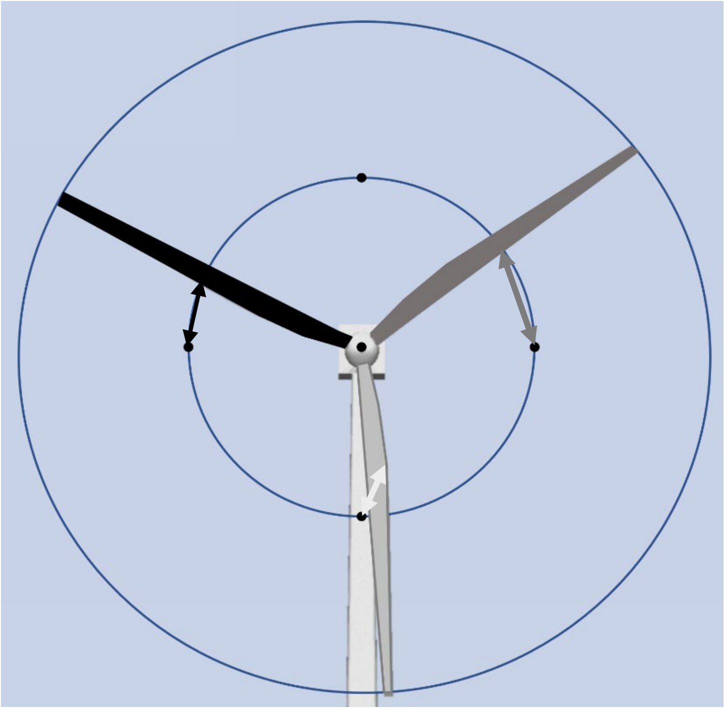
Methodologies

Feedforward individual pitch controller (FFIPC)[1]

2. Difference between the azimuth angles of the blades to each of the beams (i) is determined. Beam with the lowest difference in azimuth angle is assigned to provide the feedforward command to that blade.

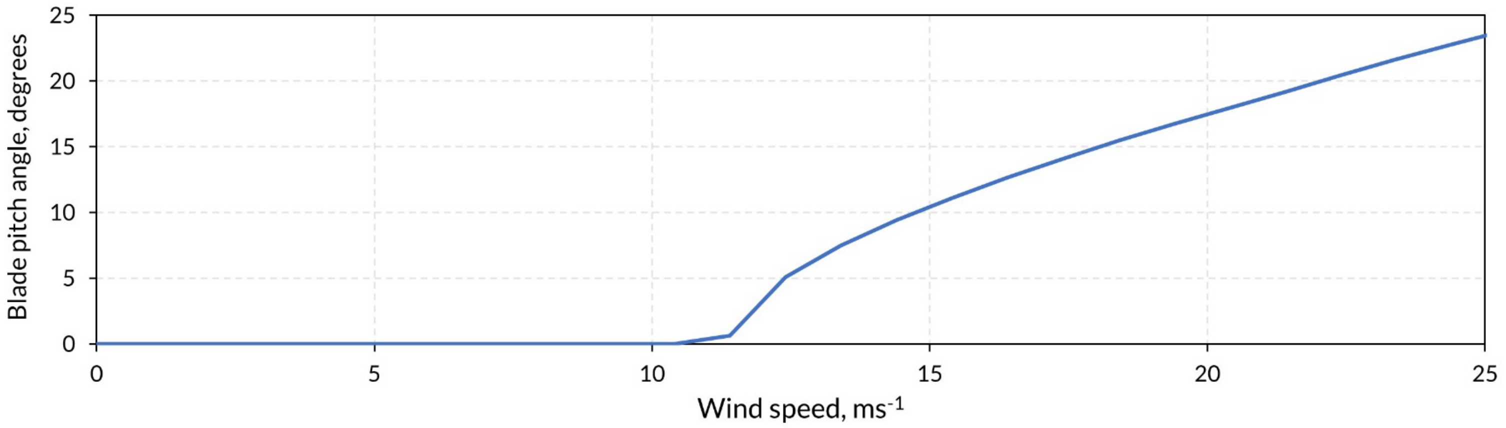
$$A_{k,dif} = A_i - A_{k,new}$$



Methodologies

Feedforward individual pitch controller (FFIPC)[1]

3. A wind speed-pitch angle look-up table is used to determine the required pitch angle ($\theta_{setpoint,\ i,}$) associated with the LIDAR-measured wind speed of the beam.



4. The error between the pitch angle set point and the average blade pitch angle is determined

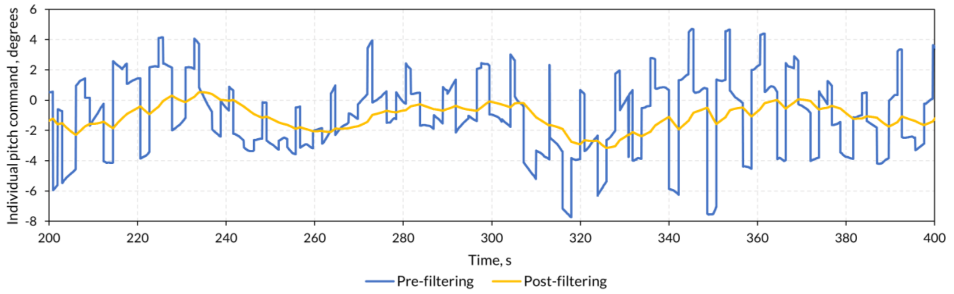
$$e_{FF,i} = \theta_{set\,point,i} - \theta_{c,avg}$$

[1] - Russell, A. J., Collu, M., McDonald, A. S., Thies, P. R., Keane, A., & Quayle, A. R. LIDAR-assisted feedforward individual pitch control of a 15 MW floating offshore wind turbine. Wind Energy. https://doi.org/10.1002/we.2891

Methodologies

Feedforward individual pitch controller (FFIPC)[1]

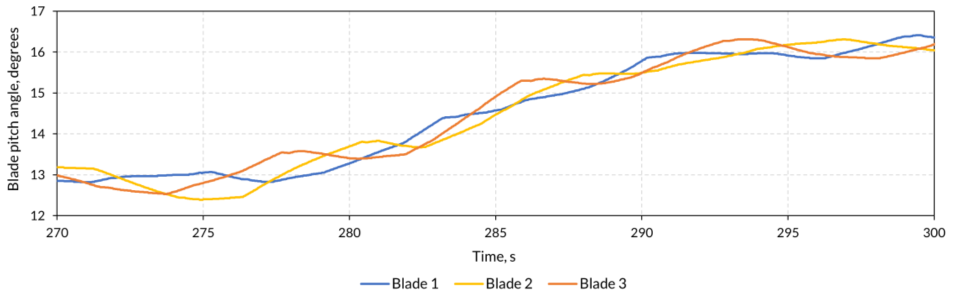
5. Individual pitch commands are low-pass filtered to prevent large variations:



6. The individual commands are combined with the feedforward collective and feedback pitch commands

$$\theta_{FF\text{-}FB,k} = (P_{FB} + I_{FF\text{-}FB}) + \theta_{TFB} + \theta_{FF,k}$$

7. This results in an individual pitch variation:



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Turbulent Wind Results

UMaine VolturnUS-S

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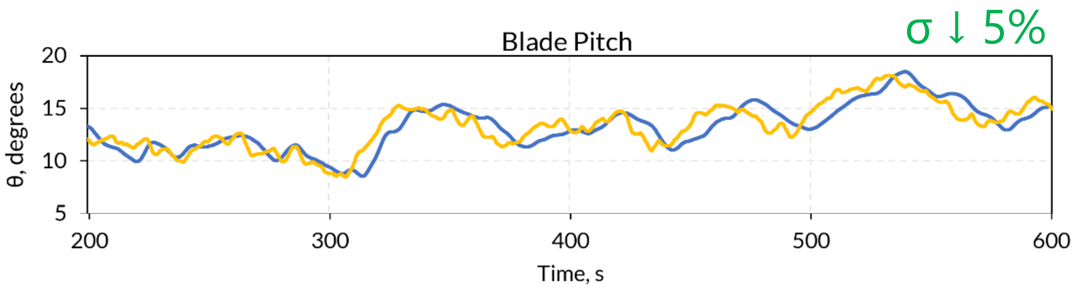
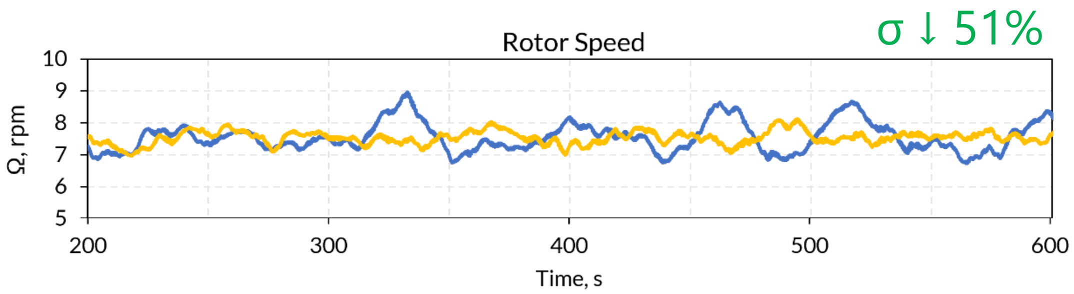
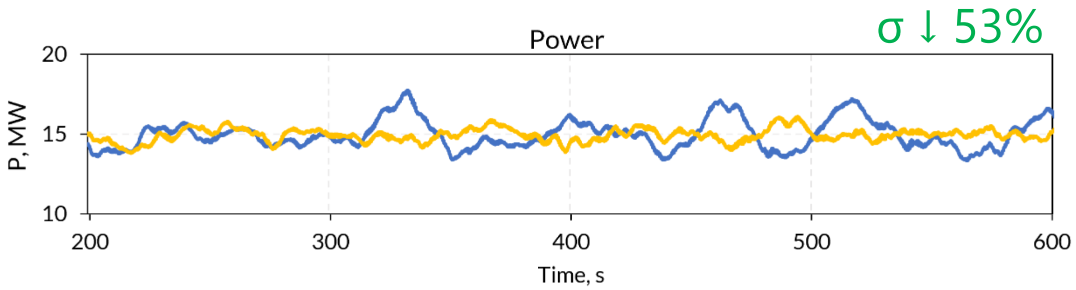
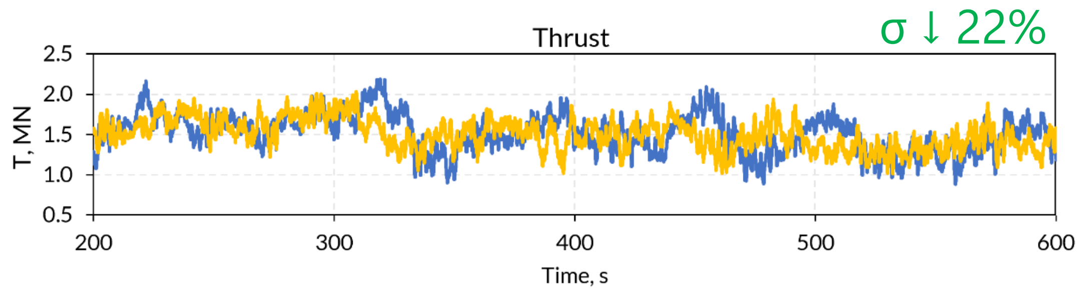
Results – VolturnUS-S

V_{avg} = 17 m/s, Irregular waves (H_s = 2.83 m, T_p= 7.85 s)









Blue – FB **Yellow** – FFCPC+FFIPC

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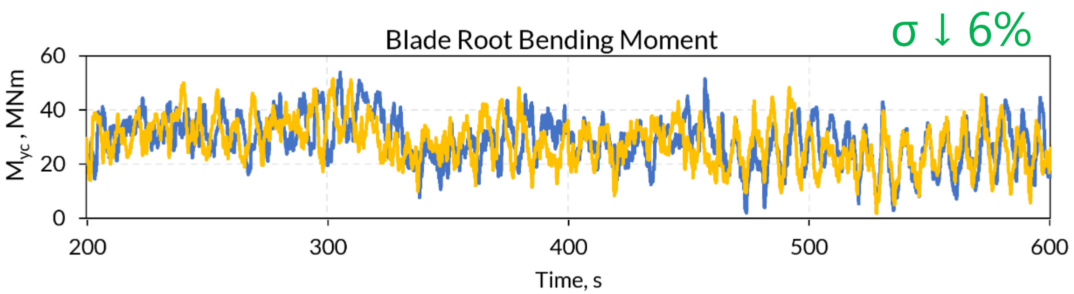

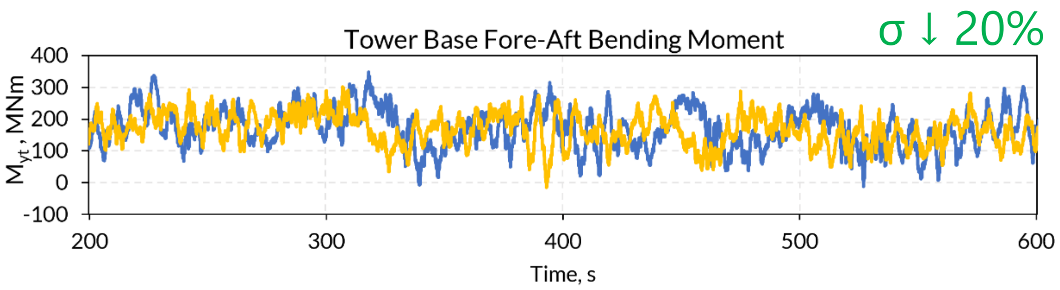

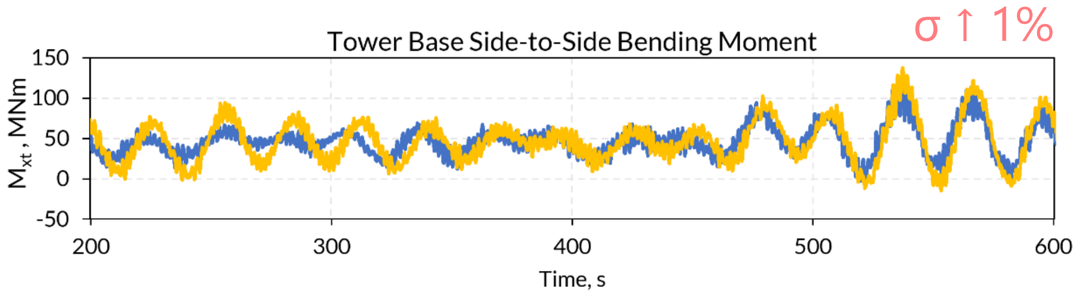

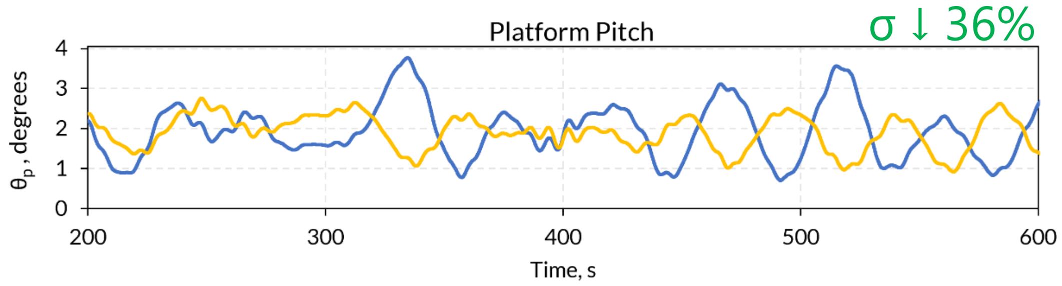

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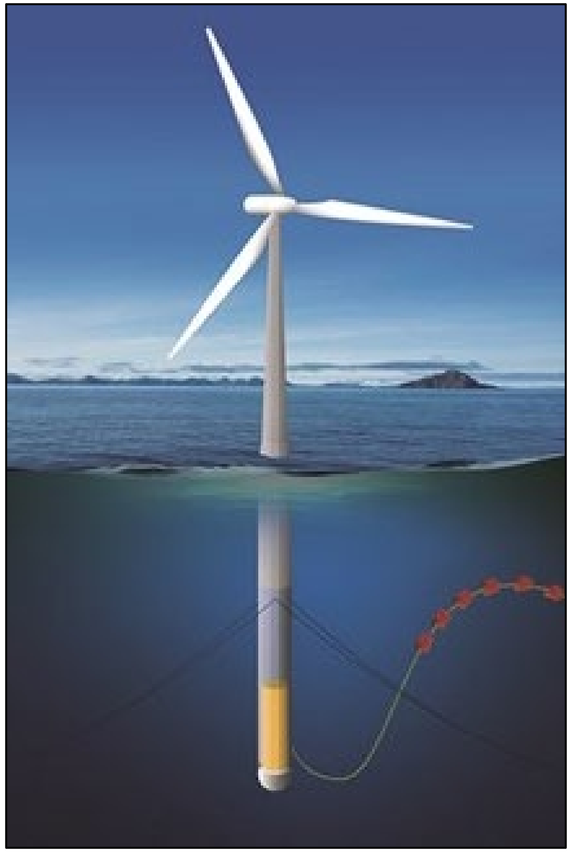
Turbulent Wind Results

WindCrete Spar



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Results – WindCrete Spar

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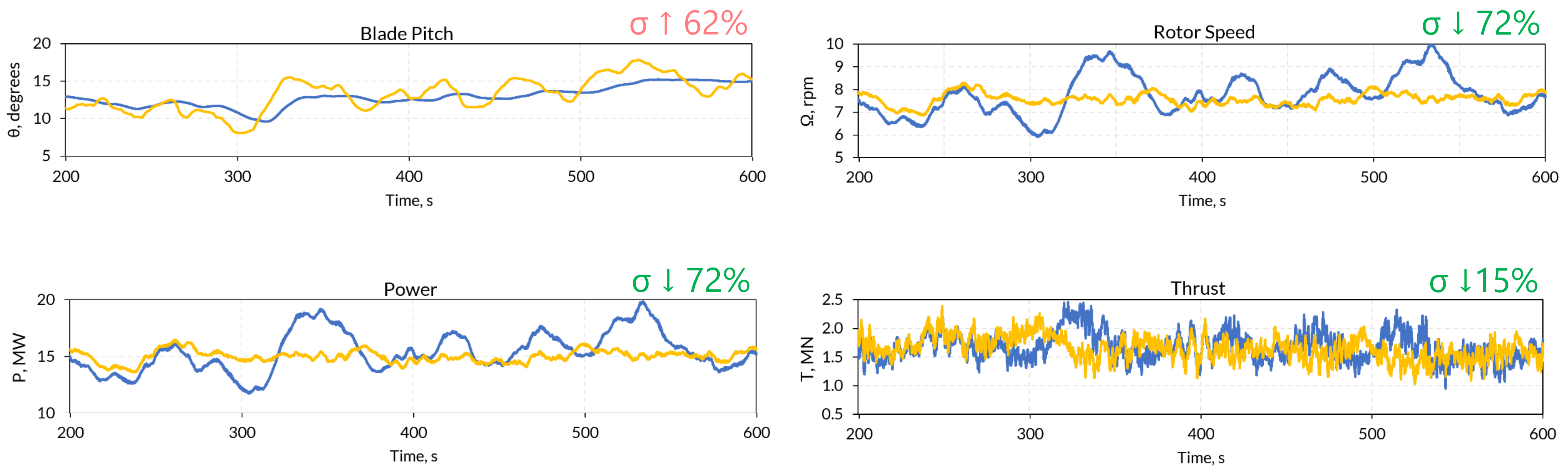

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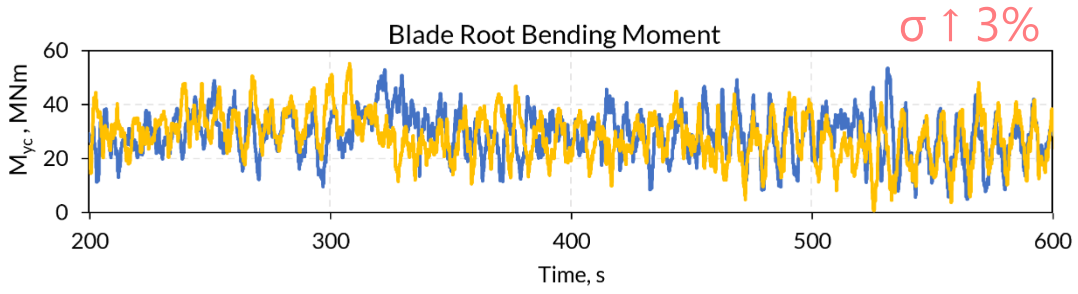

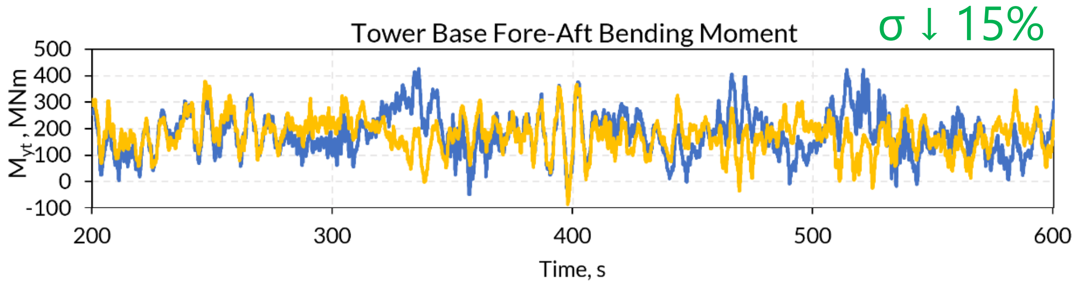

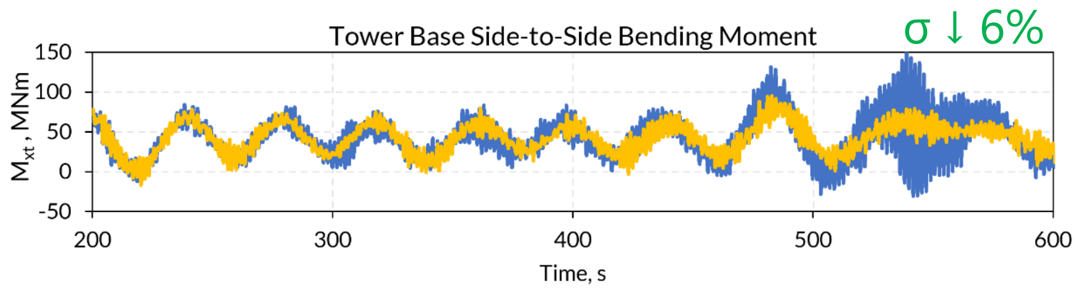

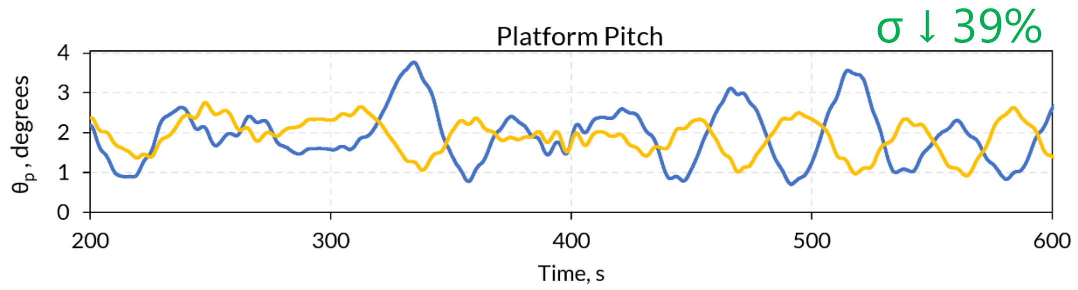

Blue – FB **Yellow** – FFCPC+FFIPC

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Results comparison

Average of 4 x 1h simulations, V_{avg} = 17 m/s, Irregular waves (H_s = 2.83 m, T_p= 7.85 s)

	Parameter	Normalised FB	VolturnUS-S Normalised Average Standard Deviation	WindCrete Spar Normalised Average Standard Deviation
Performance	Rotor speed	1.00	0.49	0.28
	Generator Power	1.00	0.47	0.28
	Blade Pitch	1.00	0.95	1.62
	Rotor Thrust	1.00	0.78	0.85
Loads	Blade Root Bending Moment	1.00	0.94	1.03
	Tower Fore-aft Bending Moment	1.00	0.80	0.85
	Tower Side-to-Side Bending Moment	1.00	1.01	0.94
Platform Motions	Yaw	1.00	1.02	0.99
	Pitch	1.00	0.64	0.61
	Roll	1.00	1.02	0.99
	Heave	1.00	1.02	0.90
	Sway	1.00	1.04	1.04
	Surge	1.00	0.76	0.65

Conclusions

Feedforward control through LIDAR wind preview can improve performance and reduce loads and platform motions for different substructure configurations

Differences were observed in the impacts on the blade pitch due to differences in feedback pitch control behaviour

Increased blade pitch activity of the WindCrete Spar did not lead to introduction of negative damping

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Thank you for your attention!

Any questions?

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