Comparing the Aerodynamic Performance of Floating Offshore Wind Turbines with Betz-Optimised and Linearised Blades

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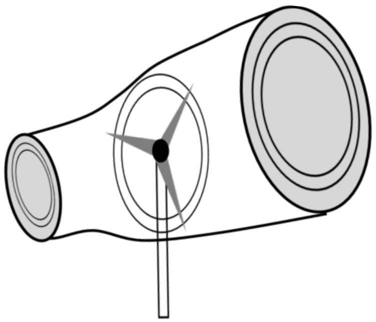
Background – Aerodynamics of Optimal Wind Turbines



- Theoretical maximum efficiency limit of a Wind Turbine as determined by Betz in 1920 based on the Rankine –Froude theory: **59.3 %**

- Same limit was derived independently around the same period by Lanchaster (1915) and Joukowski (1920). As noted by van Kuik (2017), it is more appropriate to refer to this limit as
  "***The Lanchester–Betz–Joukowsky limit***"

- More comprehensive models to determine optimal performance of wind turbines, e.g. Okulov and Sørensen (2010)

➢ No theory has to-date shown that the Betz efficiency can be exceeded
➢ All optimal rotor theories have only considered a fixed (non-surging) rotor

Floating Rotors:
- Rotor in motion due to wave induced loads
- Flow around turbine is unsteady
- Cyclic component of thrust may large compared to time-averaged value, e,g, Farrugia (2014), de Vaal (2014), Chen (2021)

Background – Design of Optimised and Linearised Blades

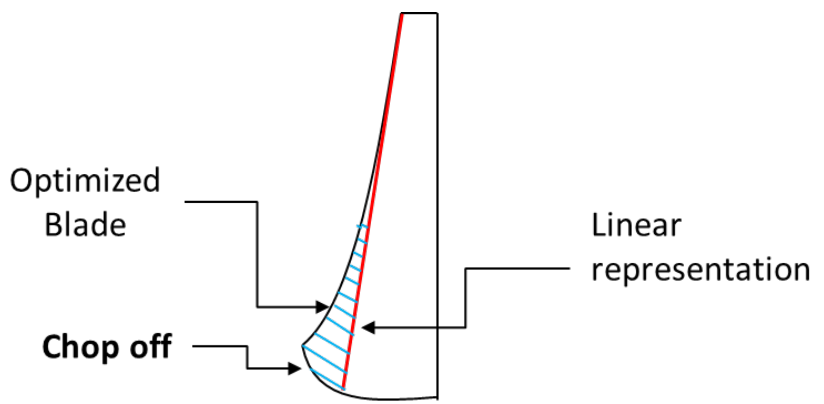
- Manwell *et al* presents two classical methods for deriving optimal blade inflow angle and chord distributions

- Both methods apply the Blade-Element-Momentum (BEM) theory and ignore drag and tip/root losses

Approach 1 (Betz optimization):
- Axial inflow factor (a1) = 1/3
- No wake rotation (a2=0)

Approach 2:
- Account for wake rotation
- Derived from derivative of the integral equation for C_P

- Both approaches assume a fixed (non-surging) rotor
- Both approaches lead to large chord and twist at the inboard sections
- The wind industry applied a linearized blade design to reduce material requirements and simplify manufacturing



Research Objective

- Using numerical modelling to investigate the influence of blade linearization on the performance of a floating offshore wind turbines

- Three and two bladed rotors considered

Code Used

❑ Free-wake Vortex Method (FWM) →**WInDS** (UMASS, *Sebastian 2012*)

❑ Model accounts for dynamic inflow and unsteady wake evolution resulting from platform motion

Designed Rotors

- Four Rotors Modelled:
  1. *Three-Bladed Optimised*
  2. *Three-Bladed Linearised*
  3. *Two-Bladed Optimised*
  4. *Two-Bladed Linearised*
- 126m diameter
- Same aerofoil type across blade

Optimised Blades

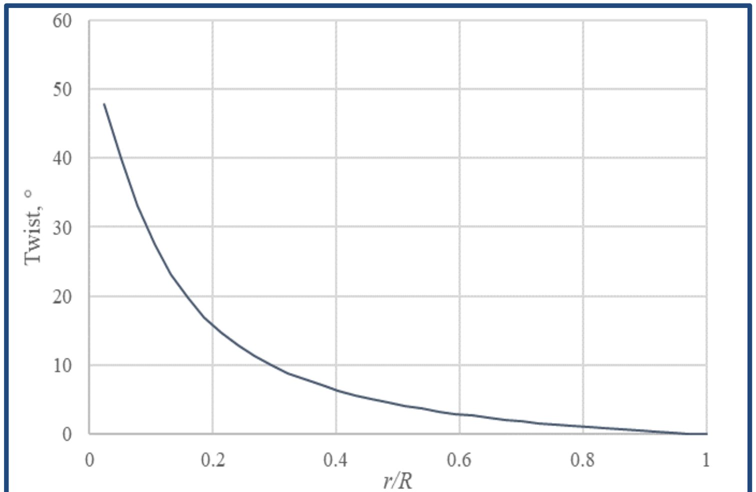
- *Manwell et al, Approach 2*

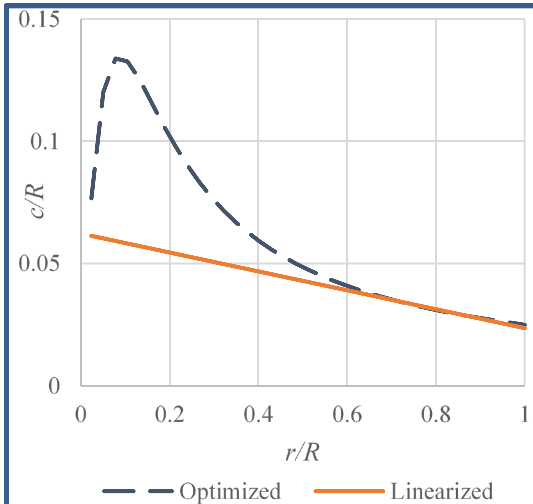
Inflow Angle: $\emptyset = \left(\frac{2}{3}\right) tan^{-1}\left(\frac{1}{\lambda_r}\right)$

Chord: $c = \frac{8\pi r}{NC_L}(1 - \cos\emptyset)$

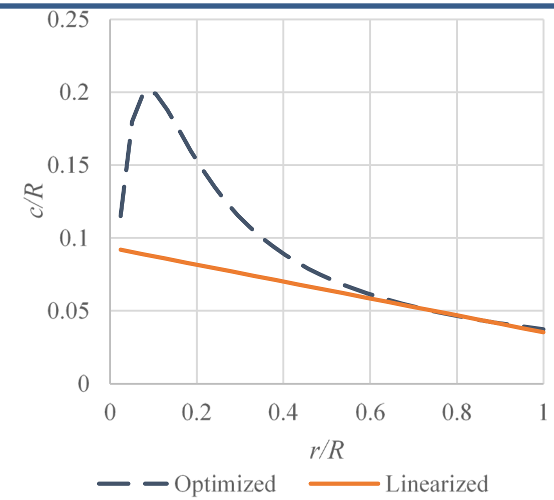
Linearized Blades

- *Chord linearized using method of Burton et al; (straight line through 70 and 90%R)*
- *Optimal blade twist retained*





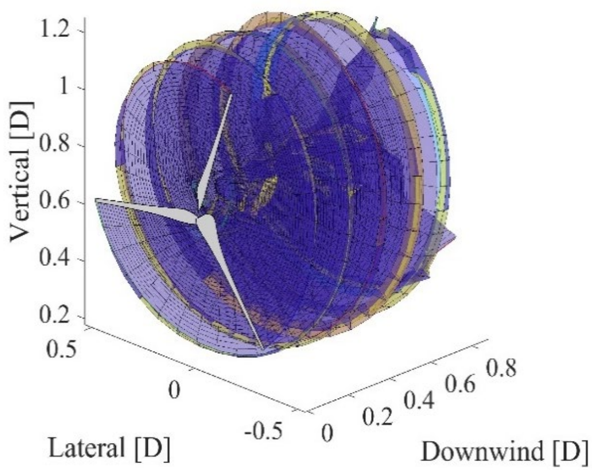
a) Three-bladed rotor designed for $\lambda_d = 8.55$



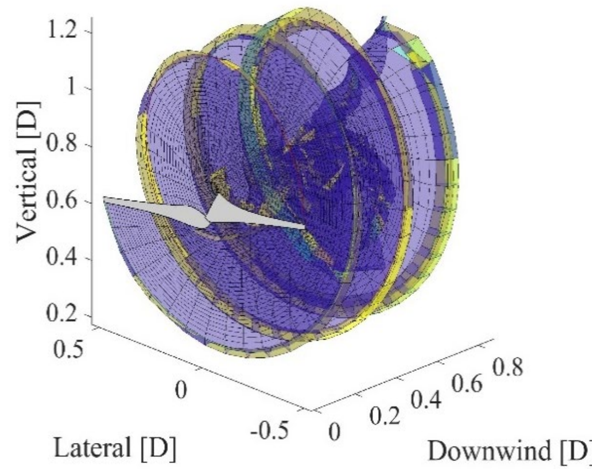
b) Two-bladed rotor designed for $\lambda_d = 8.55$

Free-wake Vortex Modelling

Optimised Blades

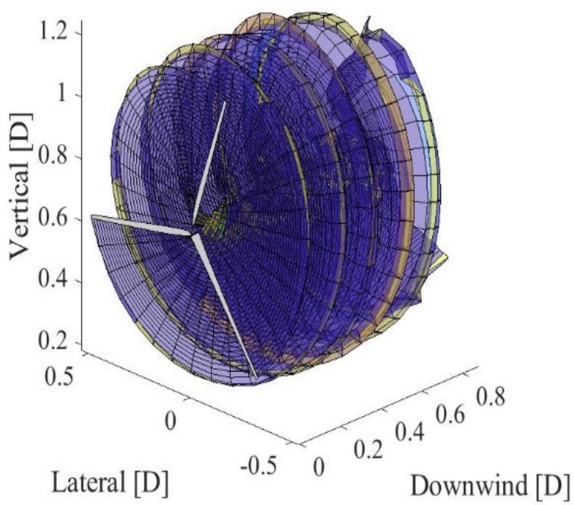


a) Designed for $\lambda_d = 8.55$, $B = 3$



b) Designed for $\lambda_d = 8.55$, B

Linearised Blades



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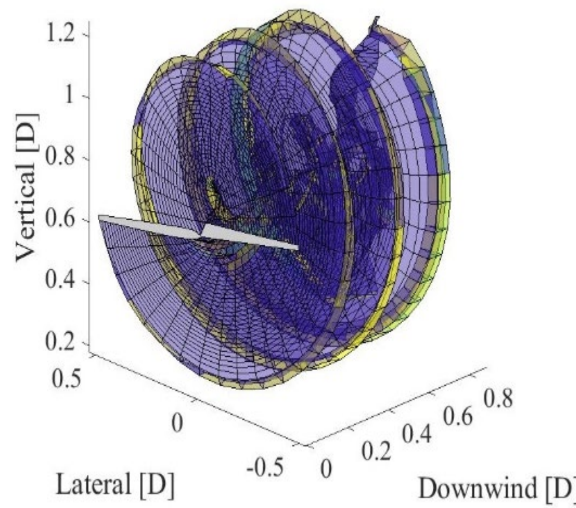


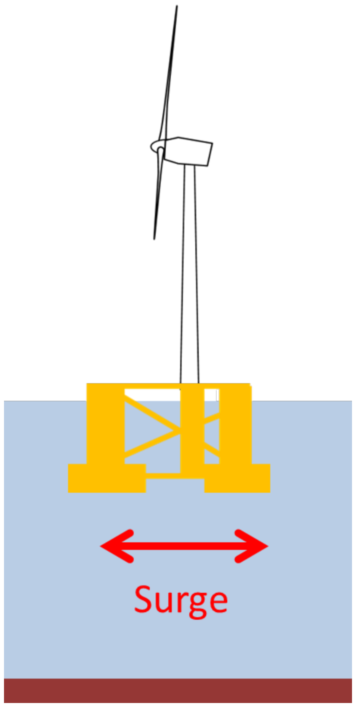
b) Designed for $\lambda_d = 8.55$, B = 2

Free-wake Vortex Modelling

Operating Conditions

- ❑ Regular wave conditions
- ❑ Windspeed fixed at 11.4m/s
- ❑ 4 Rotors x 9 Test Conditions = 36 simulations
- ❑ Blade tip pitch angle = 0 deg

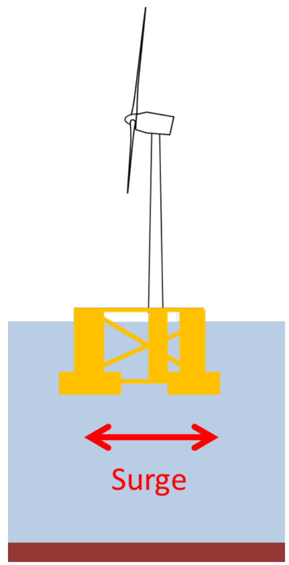
TSR	Rotor Aerodynamic State
4	Lightly Loaded
8	Loaded (Optimal efficiency)
12	Highly Loaded



$$X = A \sin(2\pi f)$$

Sea State	H_w (m)	T_w (s)	A_s (m)	V_s (m/s)
S1 (Mild)	3.66	9.5	0.75	0.5
S2 (Very Stormy)	6.4	11.65	1.85	1.0
S3 (Extreme)	9.14	13.6	3.31	1.53

Free-wake Vortex Modelling



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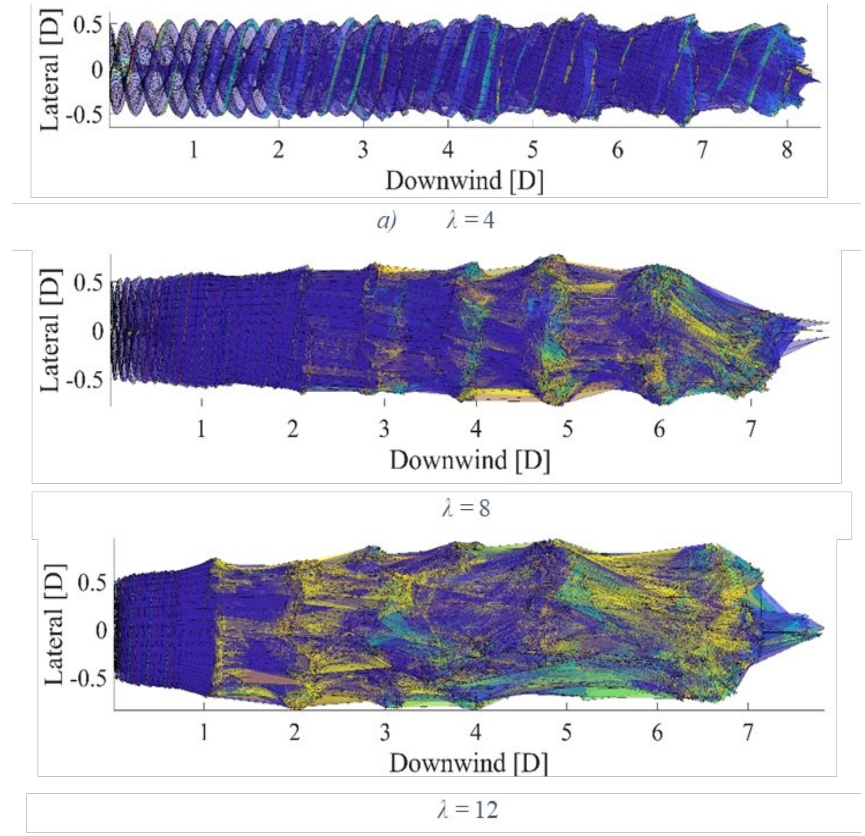
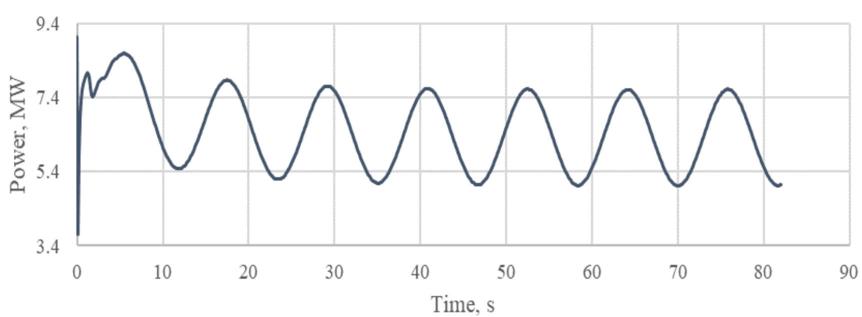
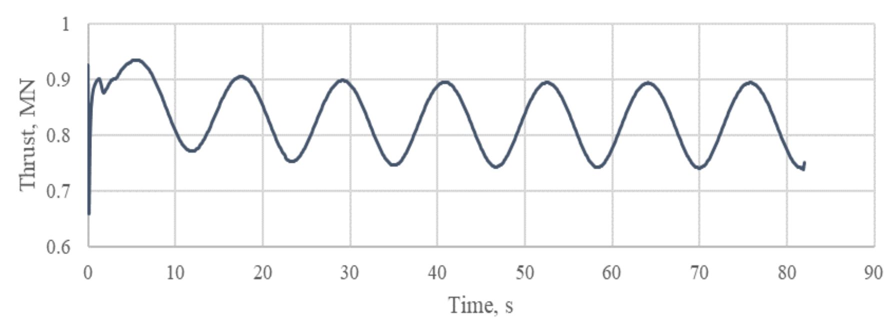
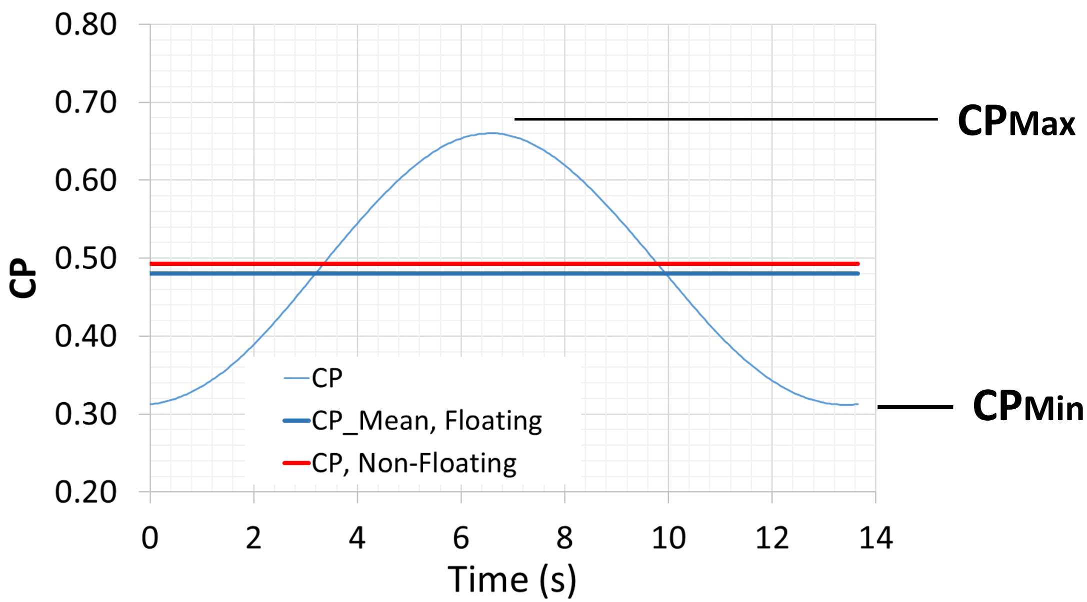






Results

Parameters for Comparison – Rotor Power



Definition of δCP and ΔCP

% Deviation in Mean CP from non-floating Conditions:

$$\delta_{CP} = \frac{CP_{Mean,F} - CP_{NF}}{CP_{NF}} \, x\, 100$$

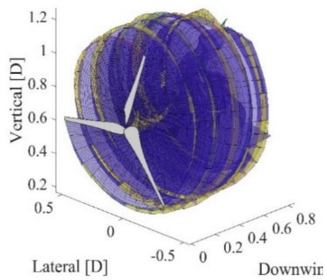
Amplitude expressed as % of the time-averaged value (mean)

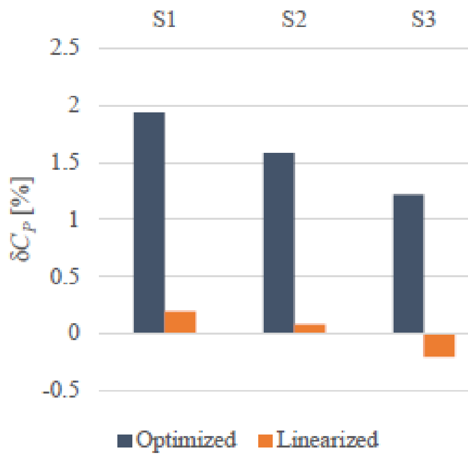
$$\Delta_{CP} = \frac{CP_{Max} - CP_{Min}}{2\, CP_{Mean,F}} \, x\, 100$$

Results

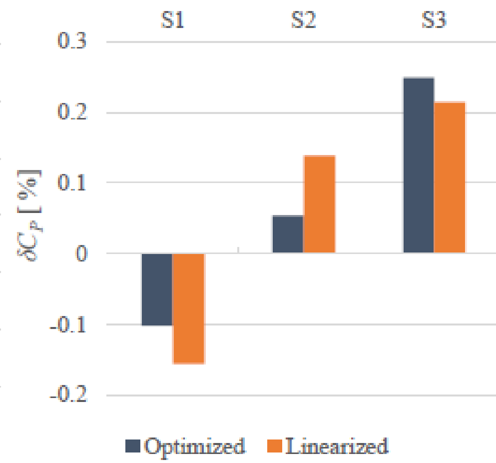
% Deviation in Mean CP from non-floating Conditions: δC_P

3-Bladed Rotor

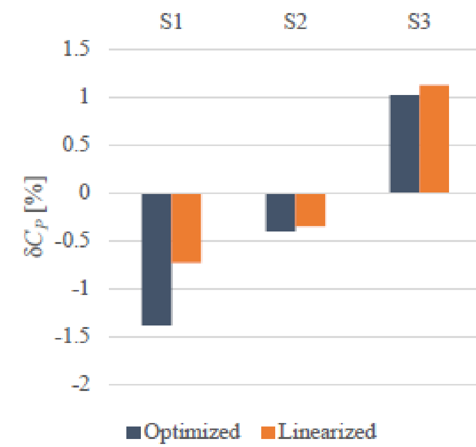




a) δC_P while operating at $\lambda = 4$

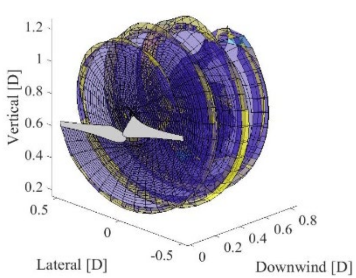


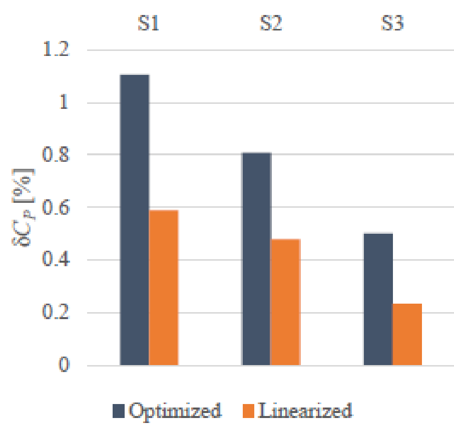
b) δC_P while operating at $\lambda = 8$



c) δC_P while operating at $\lambda = 12$

2-Bladed Rotor





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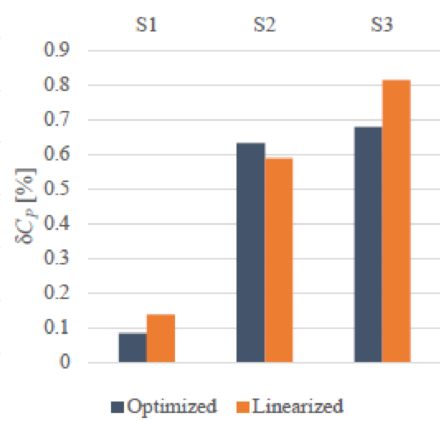
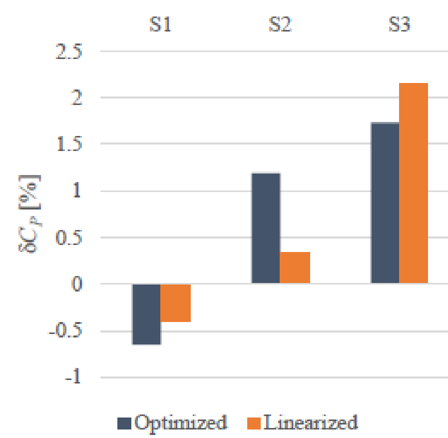


b) δC_P while operating at $\lambda = 8$

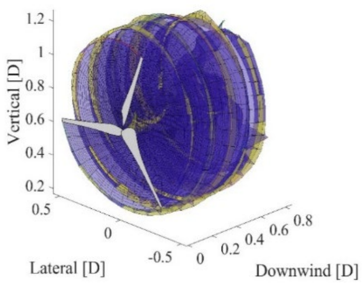


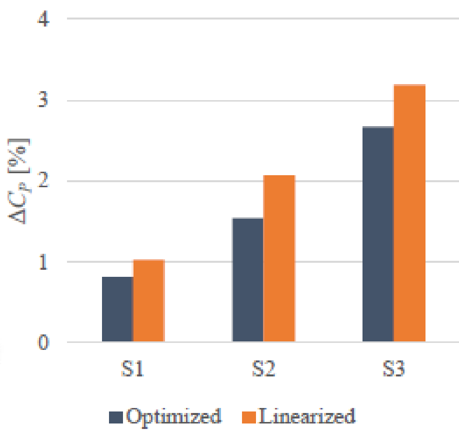
c) δC_P while operating at $\lambda = 12$

Results

Amplitude expressed as % of the time-averaged value (mean): ΔC_P

3-Bladed Rotor





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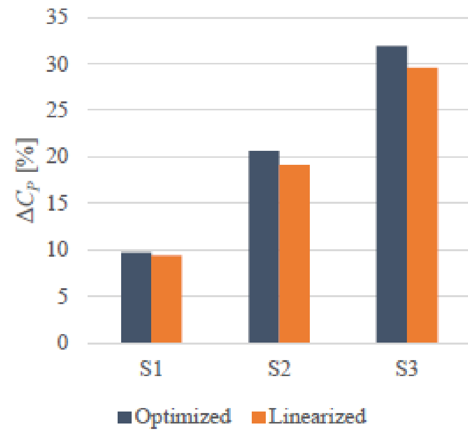

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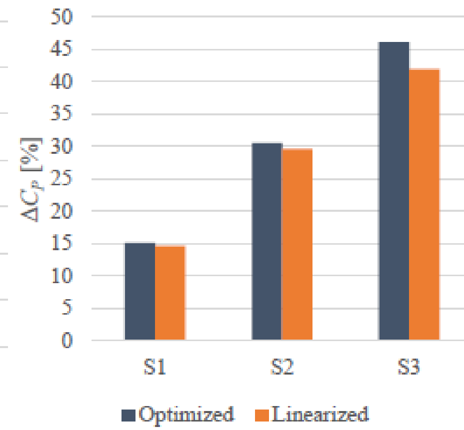
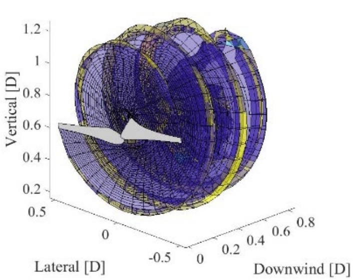
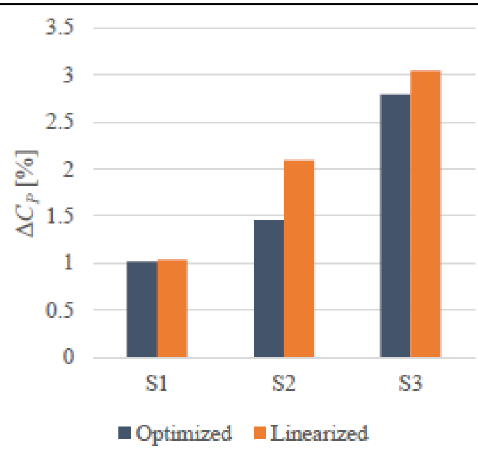


c) ΔC_P while operating at $\lambda = 12$

2-Bladed Rotor





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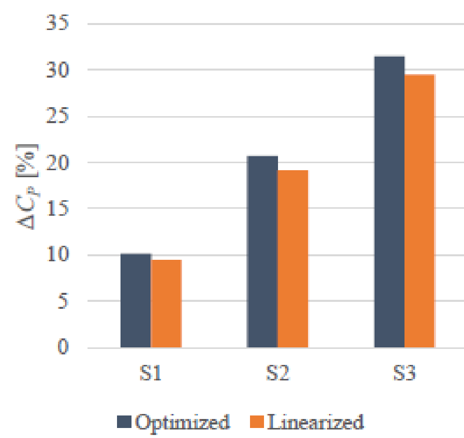

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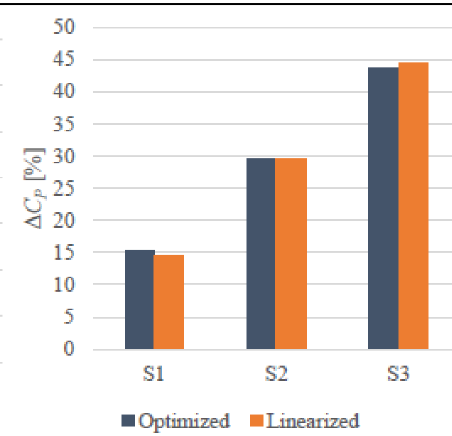
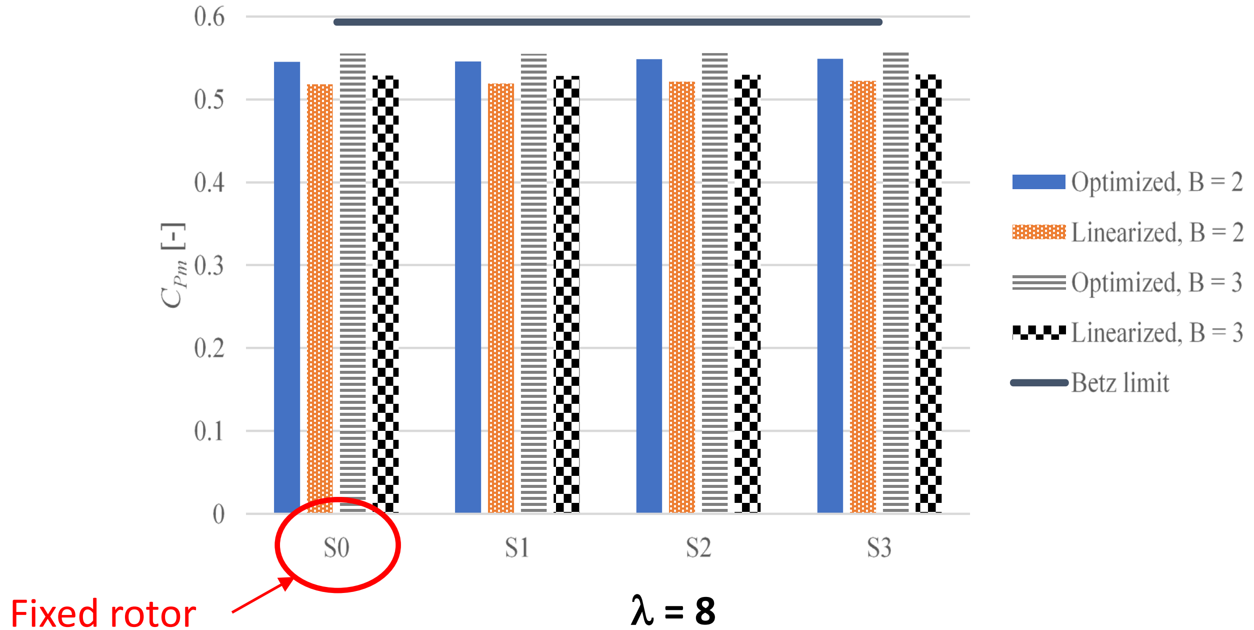


c) ΔC_P while operating at $\lambda = 12$

Results

Time-averaged value (mean) power coefficient:



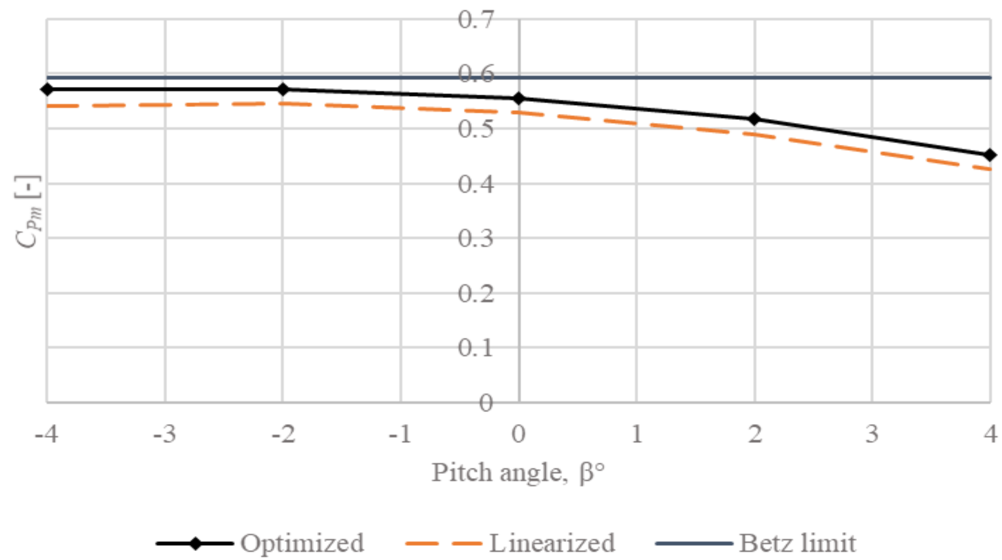
- Mean CP does not exceed the Betz limit
- Linearised three- and two-bladed rotors suffer a loss in the mean CP across all states (<5%)
- Loss in the power coefficient for floating conditions is the same as for fixed conditions
- Lower efficiency is predicted for two-bladed rotors for all sea states

Results

Effect of Linearisation at different blade pitch settings:

From: http://eng-electric.blogspot.com/2016/11/power-control-of-wind-turbines.html

Mean CP for 3-Bladed Rotors at Sea State S3, λ=8



- Loss in the mean CP though blade design linearization remains small (<5.7%) across modelled blade pitch angles

Conclusions

- The loss in efficiency resulting from blade chord linearization of floating rotors is small and has the same order of magnitude as in the case of fixed rotors. This was observed for both 3 and 2 bladed rotors.

- The time-averaged CP for a rotor with linearised blades is <5% than that of an optimised rotor across all sea states at blade pitch angle of 0 deg. The maximum loss in the time-averaged CP was <5.7% across the blade pitch range of -4 to + 4 deg.

- Differences in the amplitude-to-mean ratio for CP between optimised and linearized rotors is estimated to be minimal

- 2-bladed rotors have a lower mean CP than 3 bladed rotors at all modelled sea states

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