Aerodynamics of floating offshore wind turbines (FOWT) undergoing large motions

STEP4WIND

Training network in floating wind energy

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SIEMENS Gamesa RENEWABLE ENERGY

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Objectives

- Understand how the floater motion impacts the rotor aerodynamics in FOWT
- Assess if currently used aerodynamic models accurately capture this impact
- Upgrade current aerodynamic models and control strategies to account for the floater motion

3 Steps

1 – Low-fidelity prescribed motion simulations →

- Prescribe sinusoidal surge, pitch and yaw motions to FOWT of interest using OpenFAST and in-house SGRE aeroelastic tool
- Assess impact amplitude and frequency on Cp, Ct and local blade loads
- Estimate how far the blades are from stalling – Stall Margins

2 – High-fidelity prescribed motion simulations →

- Prescribe sinusoidal surge, pitch and yaw motions to FOWT of interest using LES tool YALES2
- Opt for an actuator line or blade resolved model depending on the stall margins
- Assess impact on Cp, Ct and local blade loads

3 – Aerodynamic model and control strategy development

- Check if the low fidelity simulations reproduce reasonably well the high fidelity simulations
- If not, improve the aerodynamic model used in the low-fidelity simulations and potentially the control strategies used

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Step 1 (current step)

- Low-fidelity prescribed motion simulations

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Process flow chart

Pre-processing inputs for platform motion:
- Active platform DOF
- Amplitude
- Frequency

Turbine OpenFAST model inputs:
- IEA 15 MW RWT + Windcrete SPAR buoy

Numerical inputs:
- Force time-histories
- Mass matrix
- Damping matrix
- Stiffness matrix
- Simulation duration
- Rotor speed
- Wind speed profile

OpenFAST 2.4

Time-series outputs:
- Power and thrust coefficients
- Angles of attack along the blades
- Platform's motions
- Spanwise load distributions (normal and tangential to rotor plane)
- Axial and tangential induction coefficients

OpenFAST parameter inputs to obtain:
- Rigid turbine
- No rotor tilt
- No control
- Rated conditions
- No tower influence on the flow
- Dynamic stall (BL)
- Uniform and steady wind

After post-processing:
- Power and thrust coefficient contours
- Stall margins, stall frequencies and percentage of the blade in stall
- Spanwise load spectras

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OpenFAST 2.4

"OpenFAST is a multi-physics, multi-fidelity tool for simulating the coupled dynamic response of wind turbines" [1], either onshore, offshore or in a floating setup

OpenFAST has several modules, each one responsible for part of the physics. The modules currently being used are:

- InflowWind – Generates the undisturbed flow field
- AeroDyn – Calculates the aerodynamic forces from the undisturbed flow field and the turbine's motion
- ExtPtfm – Converts the floating platform in a super-element of prescribed mass, damping and stiffness matrices and allows for the control of its motion by prescribing forces and moments in time
- ElastoDyn – Calculates the turbine's motion from the aerodynamic and prescribed forces

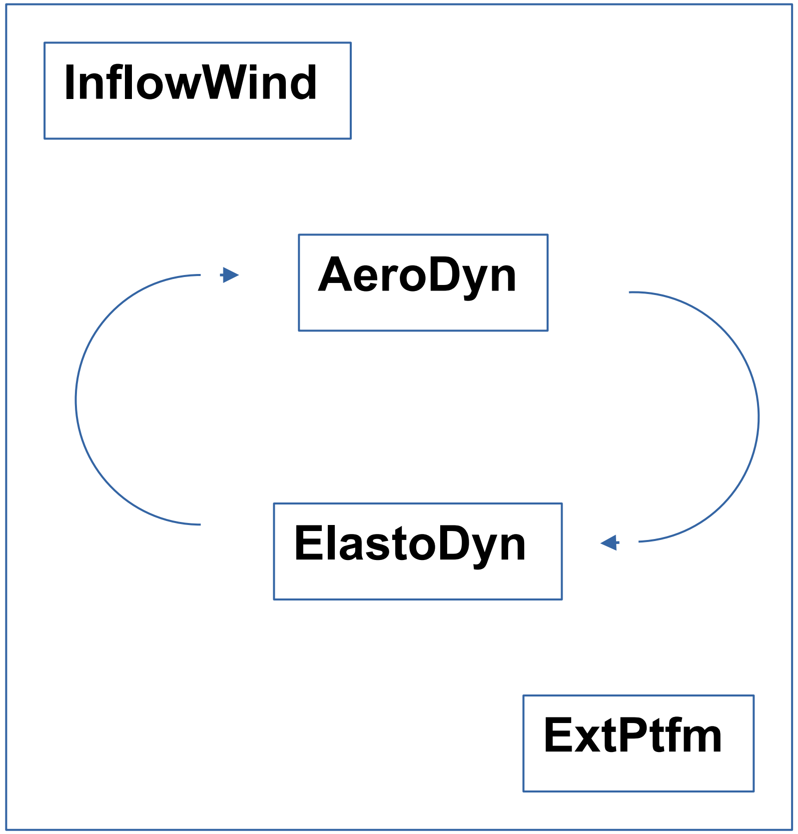

Fig. 1 – OpenFAST coupling

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Turbine OpenFAST model inputs

Model developed during the EU COREWIND project made up of:

- IEA 15 MW RWT:
  - 15 MW of rated power;
  - 240 m of rotor diameter;
  - 150 m of hub height → 135 m of hub height after incorporating SPAR
- WindCrete spar buoy

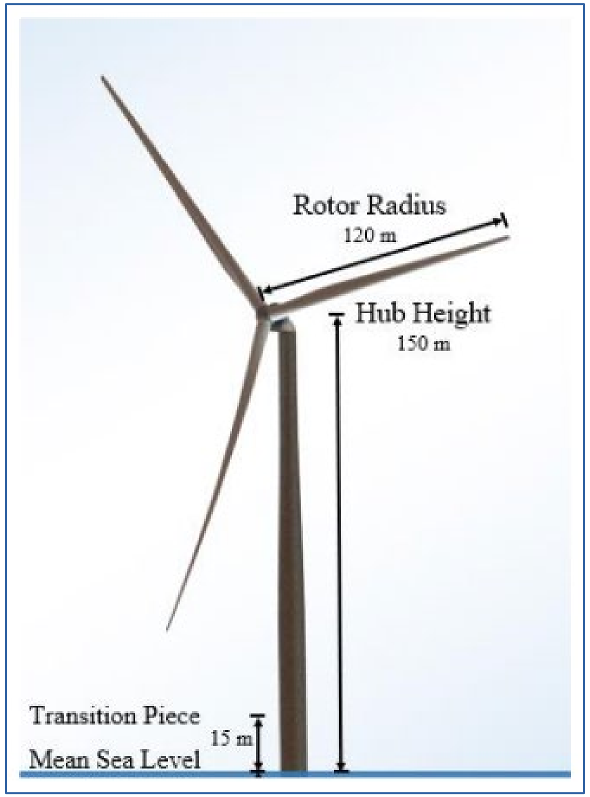

Fig. 2 – Original IEA 15 MW RWT [2]

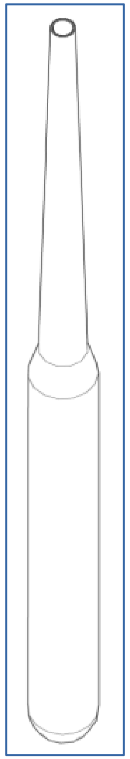

Fig. 3 – WindCrete spar buoy [2]

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OpenFAST parameters inputs

OpenFAST variables characteristic of each module which allow to choose which physical models and degrees-of-freedom are used during the simulation

→

Scenarios of different complexity can be simulated to assess the impact of the floater motion, control system and elasticity on the simulation outputs

Scenario 1
→ What is the impact of the floater motion alone on the outputs?

- Rigid turbine
- No control
- No tower influence on the flow
- Dynamic stall (BL)
- No rotor tilt
- Rated conditions
- Uniform and steady wind speed

Scenario 2
→ And considering realistic wind conditions?

- Rigid turbine
- No control
- ! Tower shadow
- Dynamic stall (BL)
- ! Rotor tilted
- ! Realistic wind conditions (turbulent inflow defined by parameters of the Tampen area in the North Sea)

Scenario 3
→ What is the impact of fixed-bottom control strategies?

- Rigid turbine
- ! Active control
- Tower shadow
- Dynamic stall (BL)
- Rotor tilted
- Realistic wind conditions (turbulent inflow defined by parameters of the Tampen area in the North Sea)

Scenario 4
→ What is the impact of elasticity?

- ! Elastic turbine
- Active control
- Tower shadow
- Dynamic stall (BL)
- Rotor tilted
- Realistic wind conditions (turbulent inflow defined by parameters of the Tampen area in the North Sea)

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Pre-processing inputs for platform motion → Numerical inputs

Platform motion is described by:

- Active degree-of-freedom
- Amplitude
- Frequency

→ Matlab class →

Linear mechanical system single DOF solution for periodic forces of constant amplitude

Produces:

- Force time histories
- Mass matrix
- Damping matrix
- Stiffness matrix

The mass/inertia in the specified degree-of-freedom is an input and must be much larger than that of the turbine

(So that the system dynamics is not affected by the aerodynamic forces and is completely driven by the force time history)

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Step 1 (current step) – Scenario 1
- Results in Surge

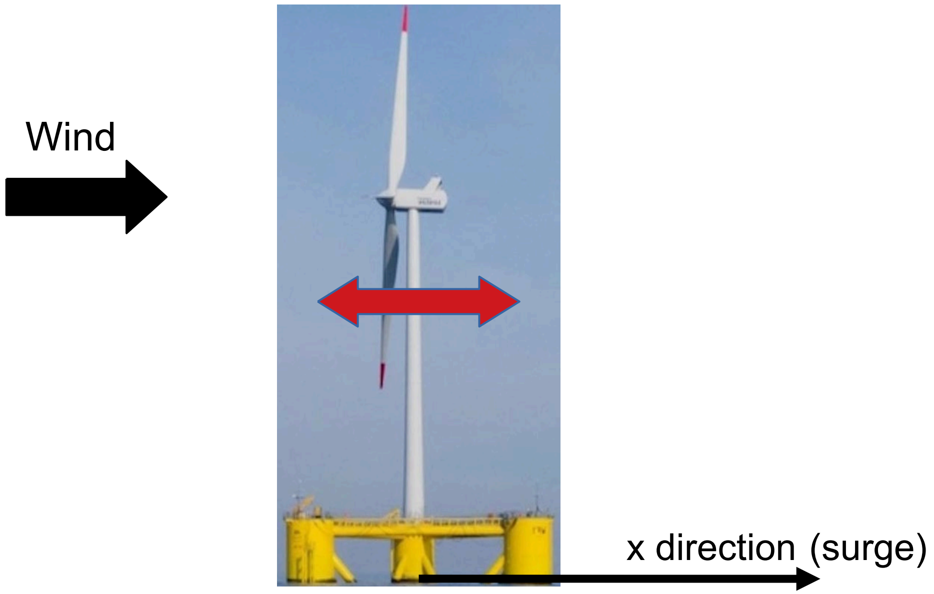
- Test matrix:
- - Frequencies ∈ [0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.08 0.1] Hz U [0.01221 0.02441 0.03052 0.09155] Hz

  - Amplitudes ∈ [0.25 0.50 0.75 1.00 2.00 3.00 4.00 6.00 8.00 10.00] m

Duration:

- 400 s (cut out transient) + 50 oscillation periods

Fig 1 – Prescribed surge motion



[3]

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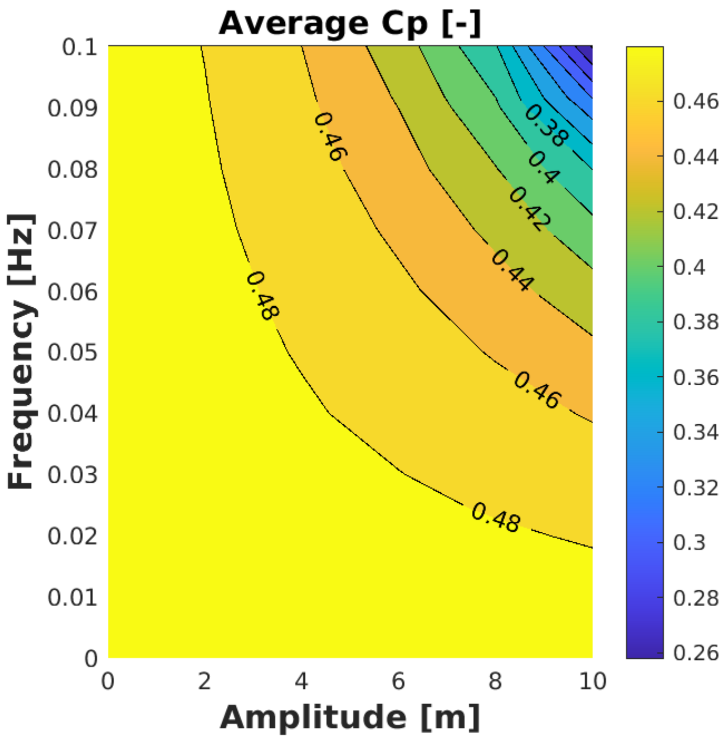
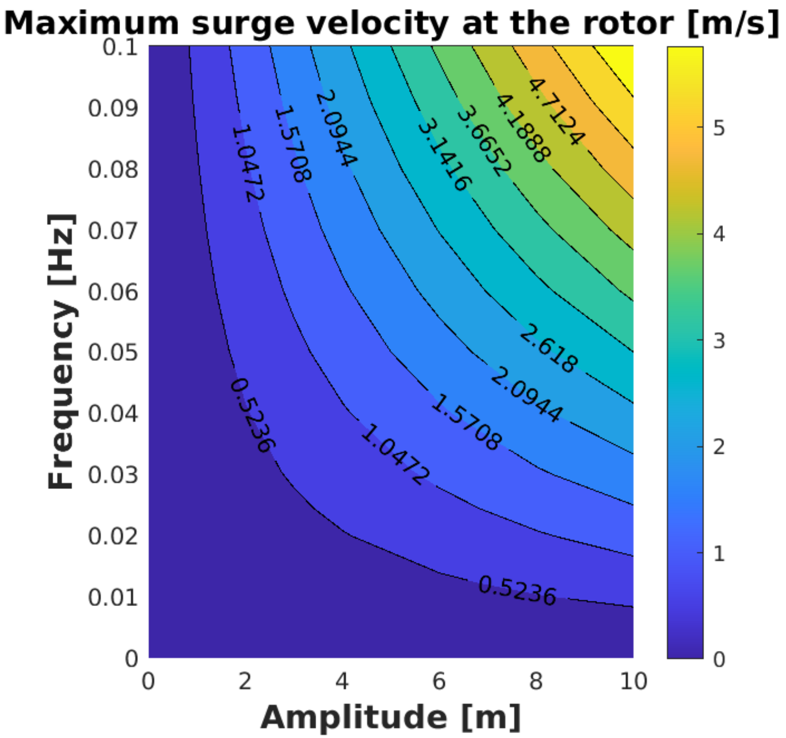
Average power coefficient contour



Steep loss in power coefficient for high amplitudes combined with high frequencies



Maximum surge velocity follows the same trend

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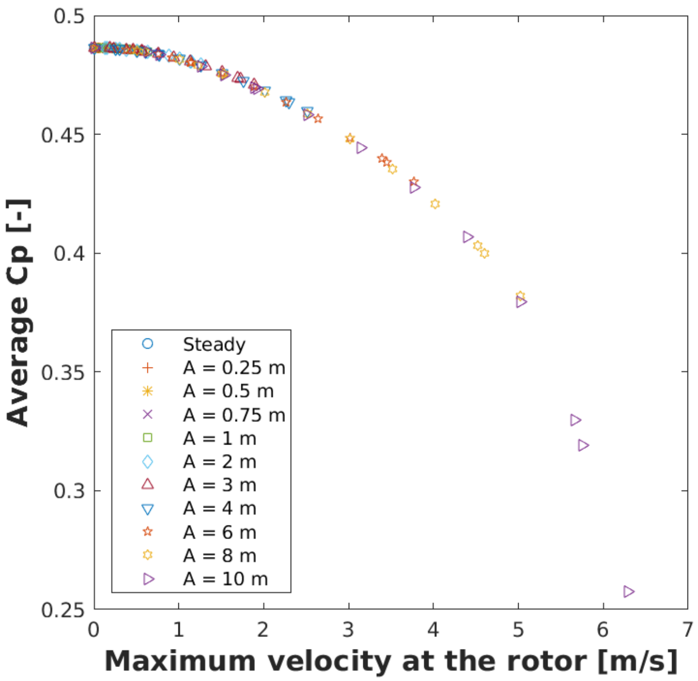
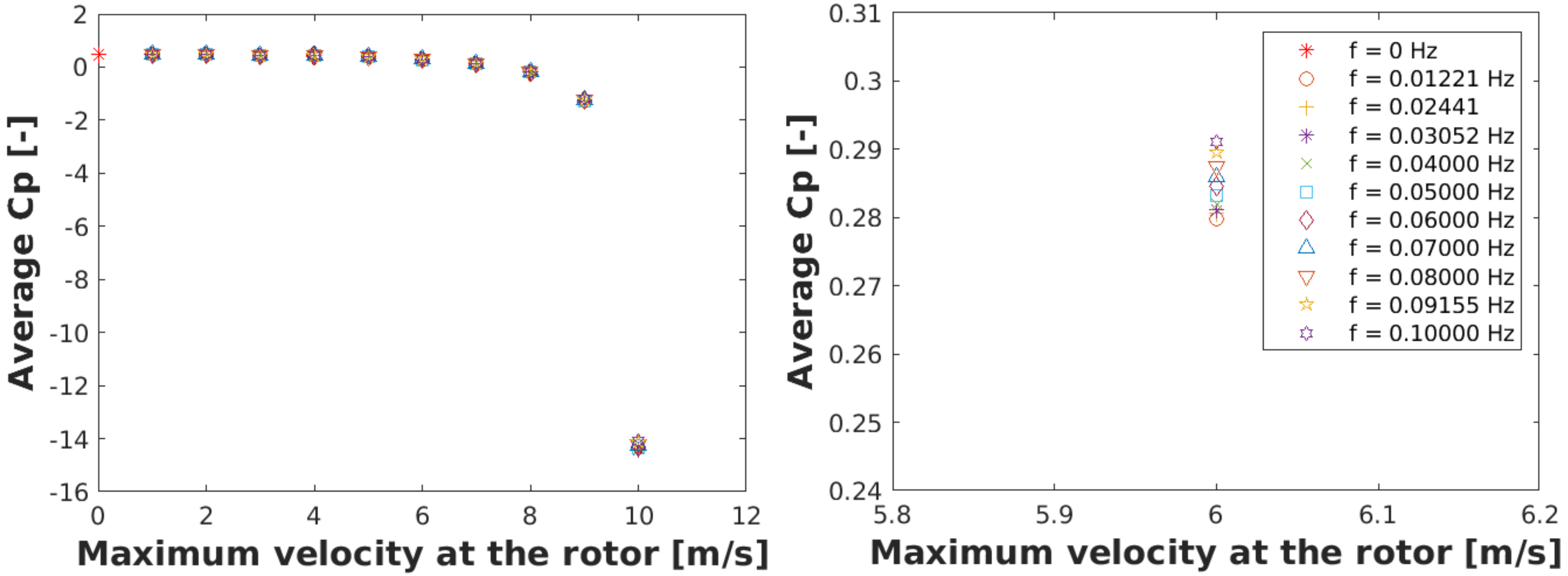
Correlation between power coefficient and maximum surge velocity



Points seem to collapse in the same curve



Trend is further confirmed

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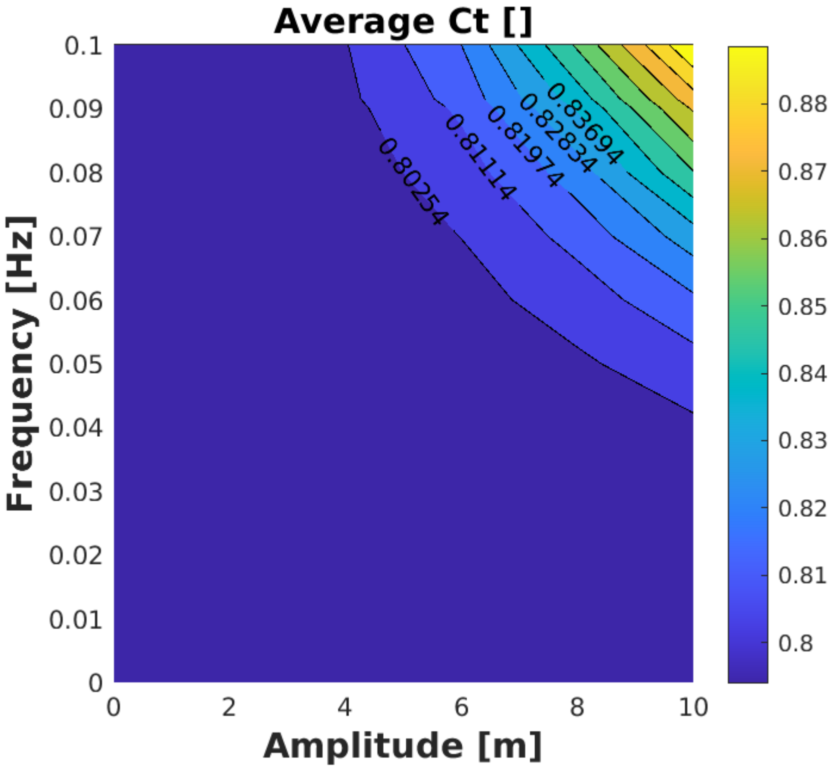
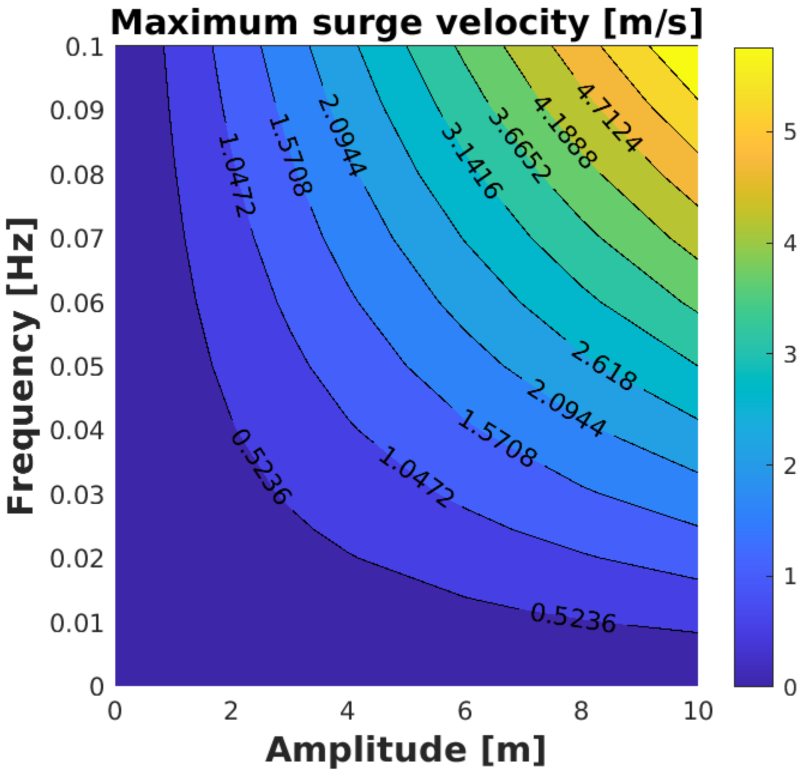
Average thrust coefficient contour



Moderate increase in thrust coefficient for high amplitudes combined with high frequencies



Maximum surge velocity follows the same trend

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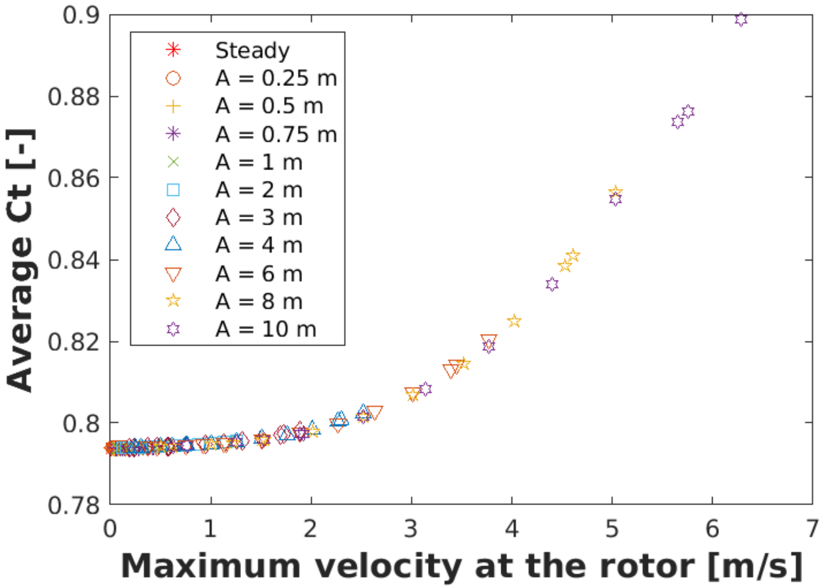
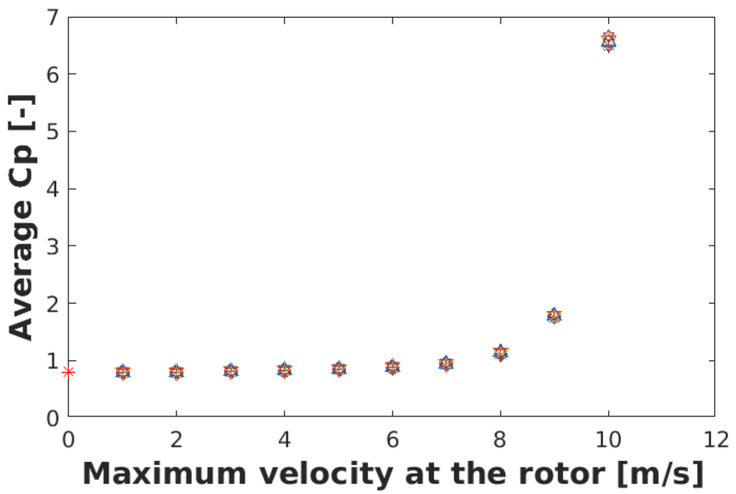
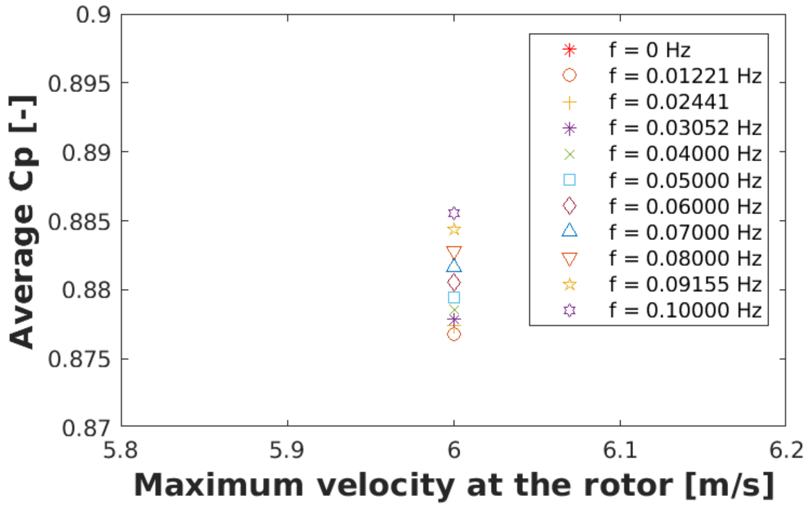
Correlation between thrust coefficient and maximum surge velocity







Trend is further confirmed

Points seem to collapse in the same curve

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Next steps

- Optimize simulation duration and number of output variables
- Simulate more adequate amplitude range
- Consider scenarios of increased complexity – Realistic wind conditions, control and elasticity
- Expand the analysis to pitch considering several pitch offsets (due to the thrust on the rotor)
- Expand the analysis to yaw

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Thank you for your attention

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Percentage of the blade in stall, stall margin and stall frequecy

<table>
<tr><th>Frequency [Hz] \ Amplitude [m]</th><th>0</th><th>0.25</th><th>0.5</th><th>0.75</th><th>1</th><th>2</th><th>3</th><th>4</th><th>6</th><th>8</th><th>10</th></tr>
<tr><td>0.1</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>19.79|-0.39</td><td>22.29|-0.82</td><td>31.25|-1.79</td><td>33.37|-2.86</td><td>29.10|-2.92</td><td>29.49|-3.31</td></tr>
<tr><td>0.09155</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>15.09|-0.21</td><td>29.65|-1.16</td><td>28.89|-1.46</td><td>31.32|-2.43</td><td>24.55|-2.44</td><td>26.23|-2.76</td></tr>
<tr><td>0.09</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>14.10|-0.18</td><td>29.43|-1.12</td><td>28.61|-1.40</td><td>31.09|-2.35</td><td>30.34|-2.96</td><td>25.31|-2.66</td></tr>
<tr><td>0.08</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>26.32|-0.80</td><td>24.91|-1.02</td><td>27.73|-1.82</td><td>34.59|-3.19</td><td>29.09|-2.93</td></tr>
<tr><td>0.07</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>21.81|-0.49</td><td>17.71|-0.63</td><td>32.25|-1.99</td><td>31.94|-2.52</td><td>29.36|-2.81</td></tr>
<tr><td>0.06</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>14.08|-0.18</td><td>26.30|-0.80</td><td>28.61|-1.40</td><td>27.74|-1.82</td><td>33.39|-2.86</td></tr>
<tr><td>0.05</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>19.79|-0.38</td><td>22.24|-0.82</td><td>31.23|-1.79</td><td>29.03|-2.00</td></tr>
<tr><td>0.04</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>26.32|-0.80</td><td>24.91|-1.02</td><td>31.20|-1.80</td></tr>
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<tr><td>0.03</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>14.08|-0.18</td><td>26.30|-0.80</td><td>22.23|-0.82</td></tr>
<tr><td>0.02441</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>18.60|-0.34</td><td>26.69|-0.84</td></tr>
<tr><td>0.02</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>19.77|-0.38</td></tr>
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<tr><td>0</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td><td>0.00|+0.00</td></tr>
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Frequency [Hz]

Amplitude [m]

Blade fraction in stall [%] (colour scale: 0, 5, 10, 15, 20, 25)

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References:

[1] - https://openfast.readthedocs.io/en/main/

[2] - Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. Definition of the IEA 15-Megawatt Offshore Reference Wind. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698. https://www.nrel.gov/docs/fy20osti/75698.pdf

[3] – Principal Power

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