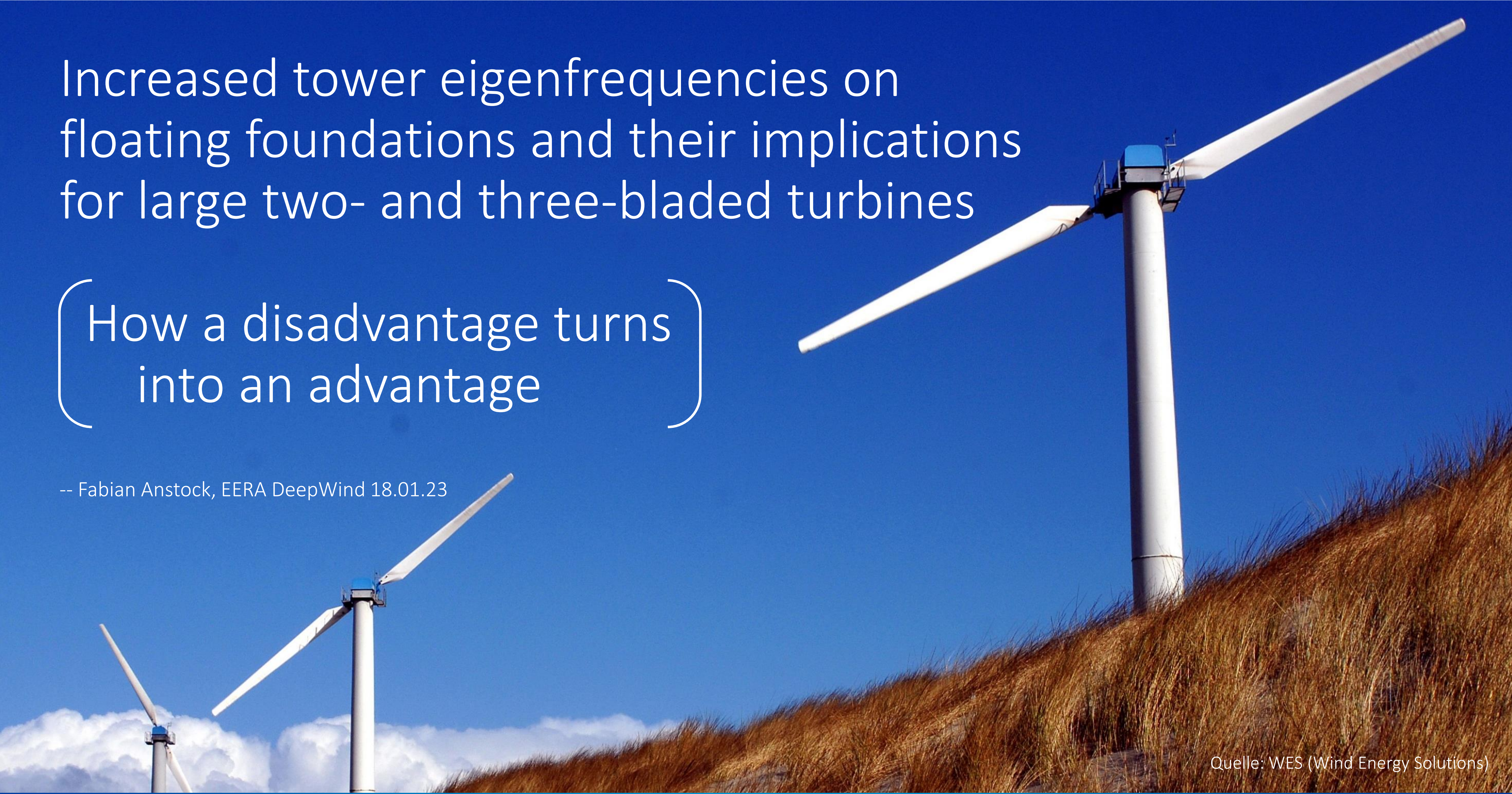
Increased tower eigenfrequencies on floating foundations and their implications for large two- and three-bladed turbines

How a disadvantage turns into an advantage

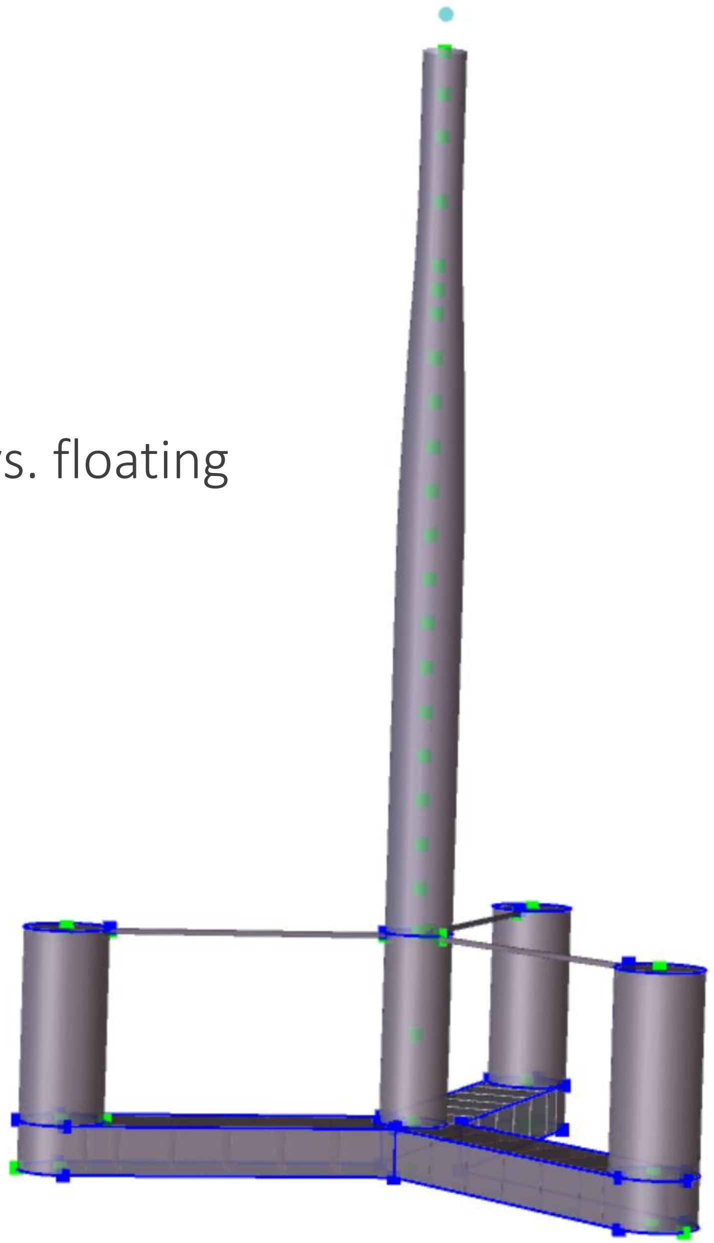
-- Fabian Anstock, EERA DeepWind 18.01.23



Quelle: WES (Wind Energy Solutions)

Agenda

1. Two-bladed reference turbine
2. Load comparison 2B vs. 3B for bottom-fixed
3. Campbell-Diagram for tower eigenfrequency: bottom-fixed vs. floating
4. Summary



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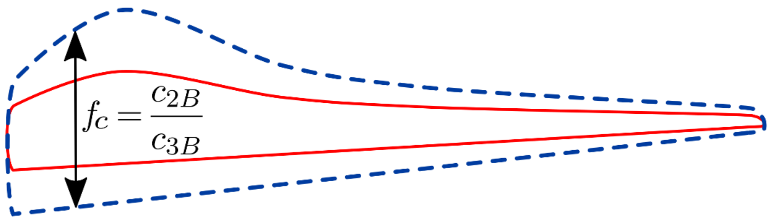
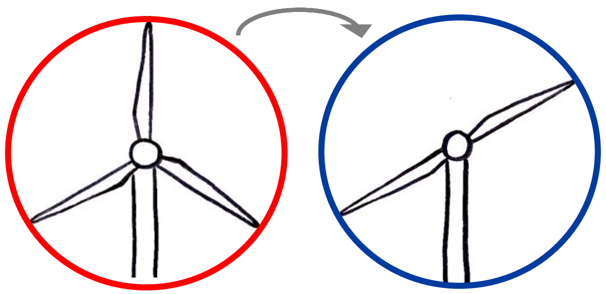
1) Two-bladed turbine from a three-bladed reference (20MW INNWIND)

Most comparable two-bladed turbine:

➢ **Equal aerodynamics**[1] (same airfoils, AoA, and relative chord lengths)





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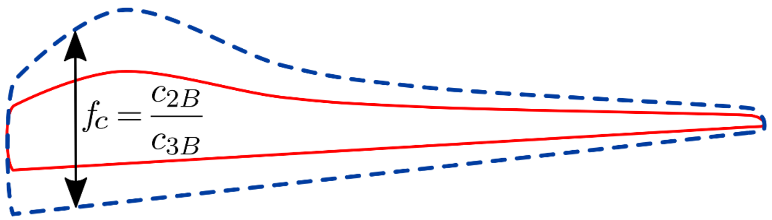

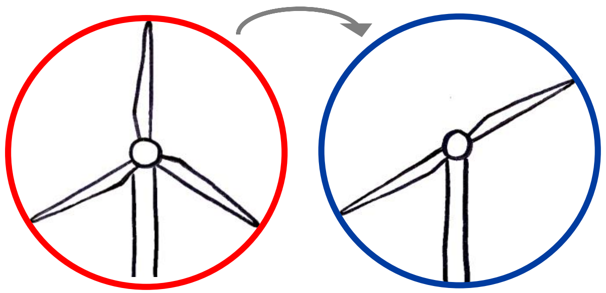

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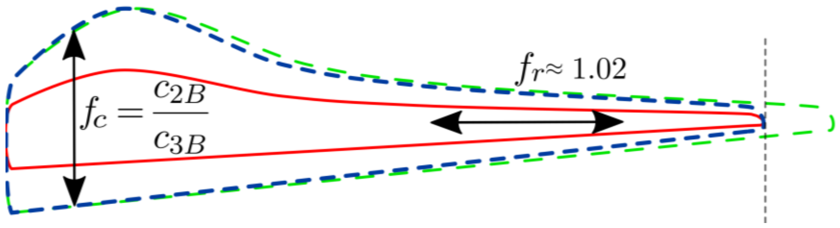

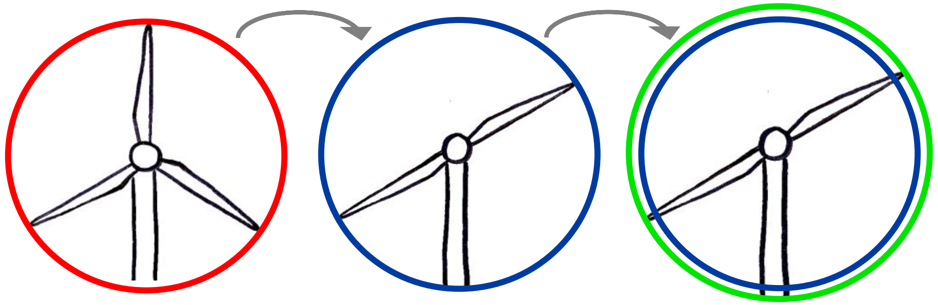

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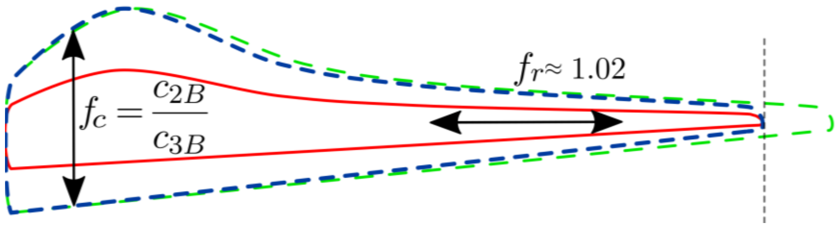

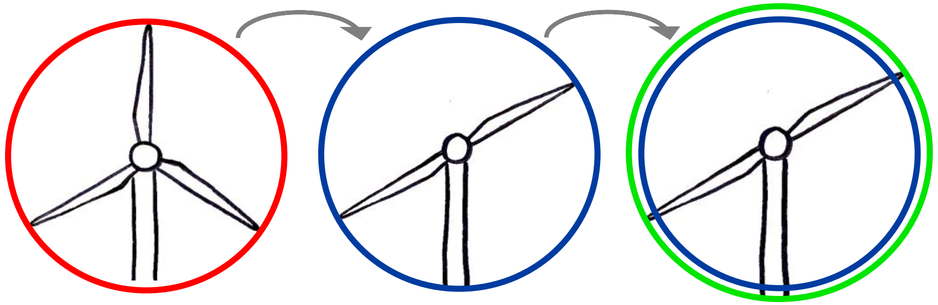

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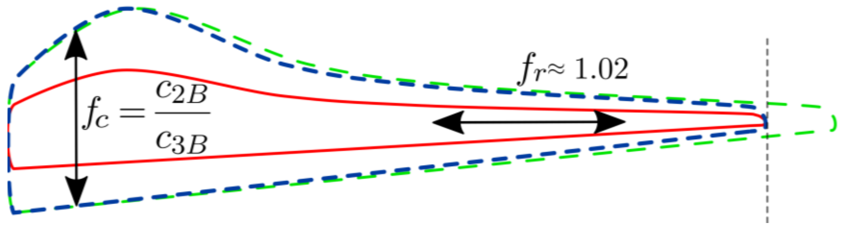

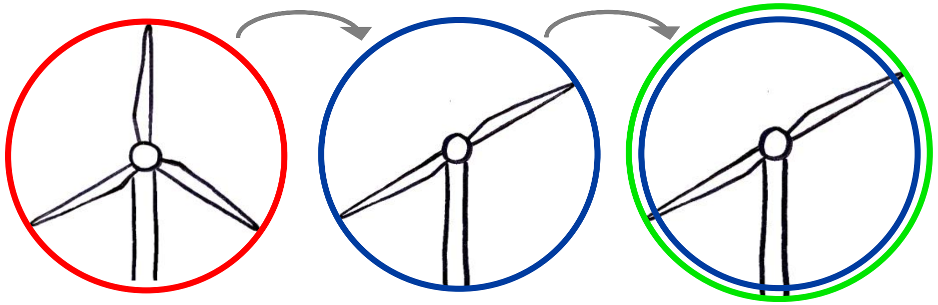

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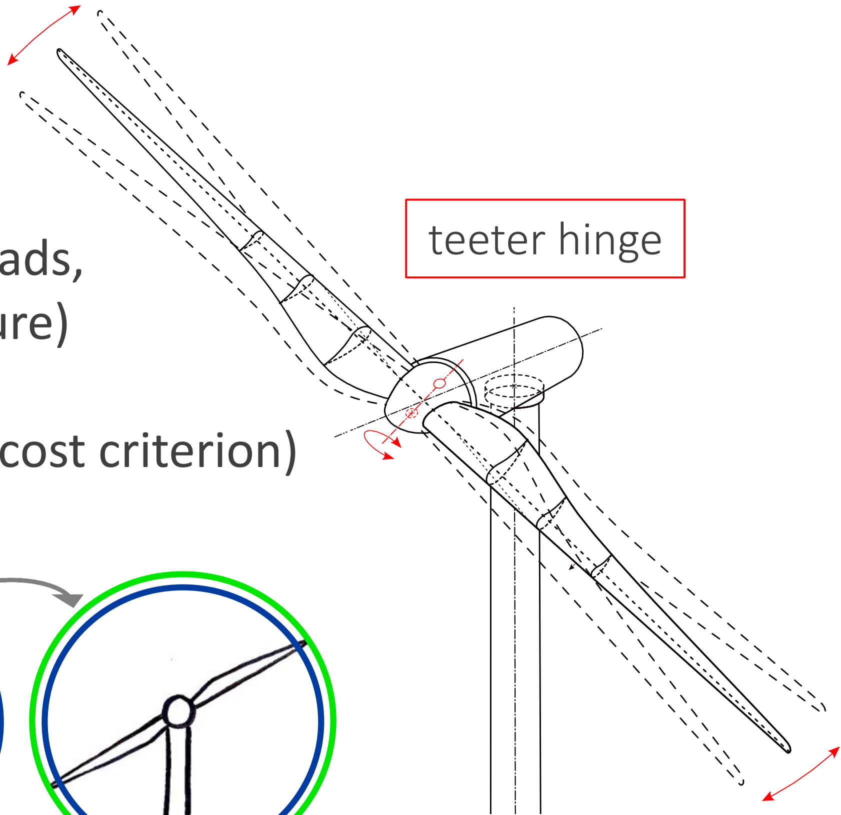

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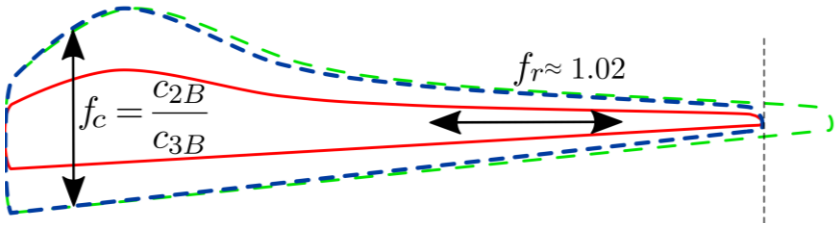

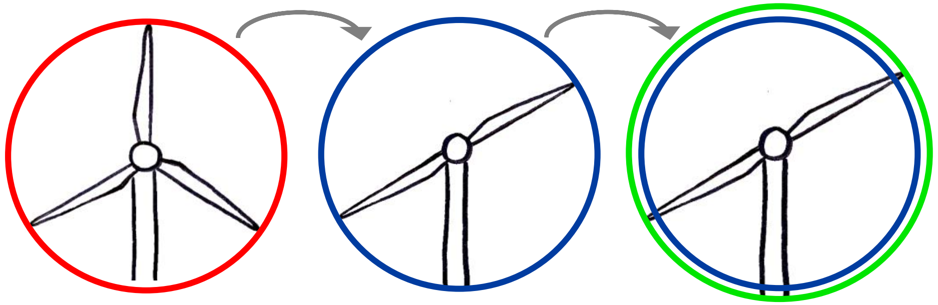

Variants:

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2B teeter (like 2B twin but with a teeter hinge)

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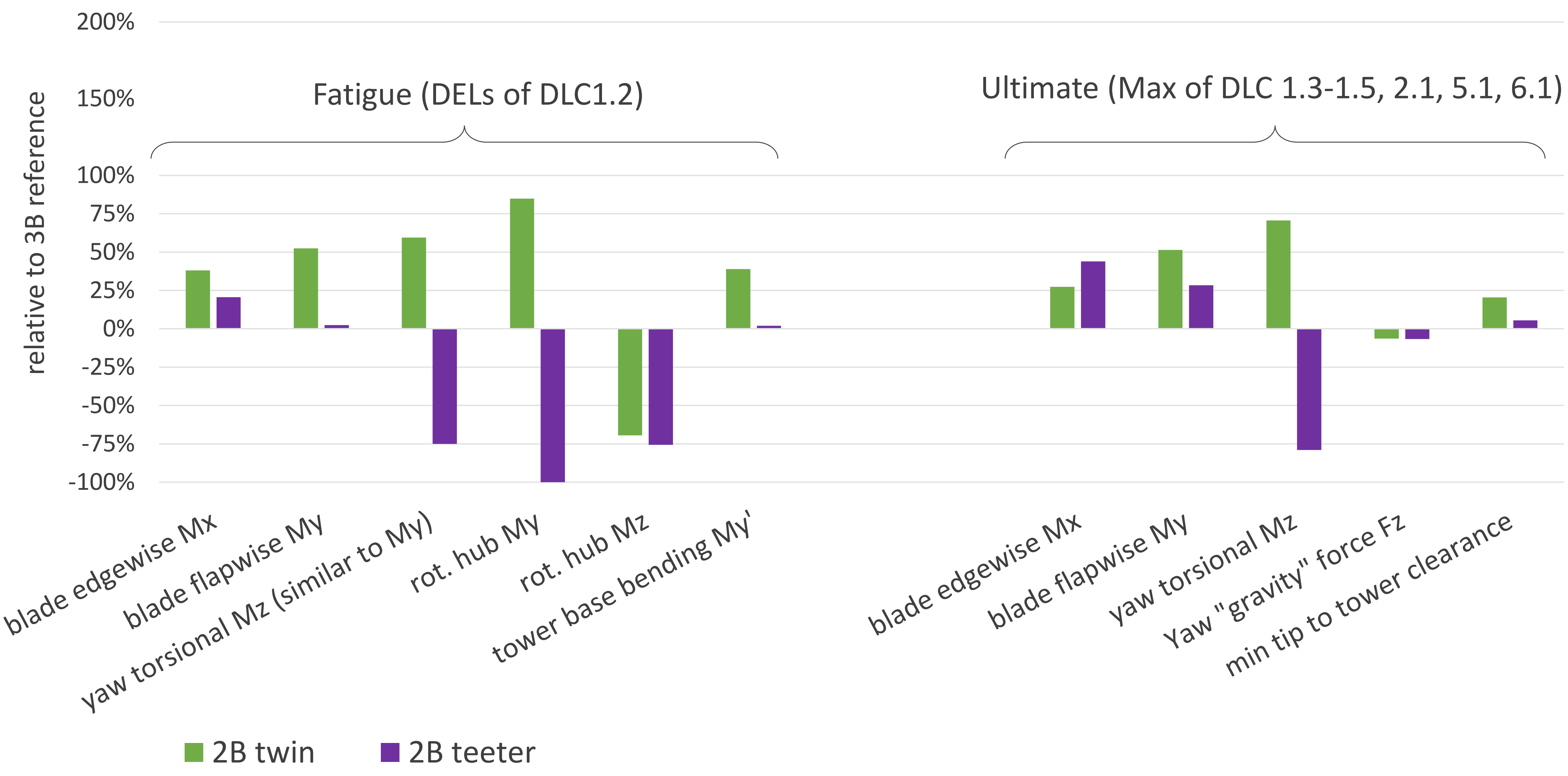
1) Load difference compared to the three-bladed reference (3B ref)



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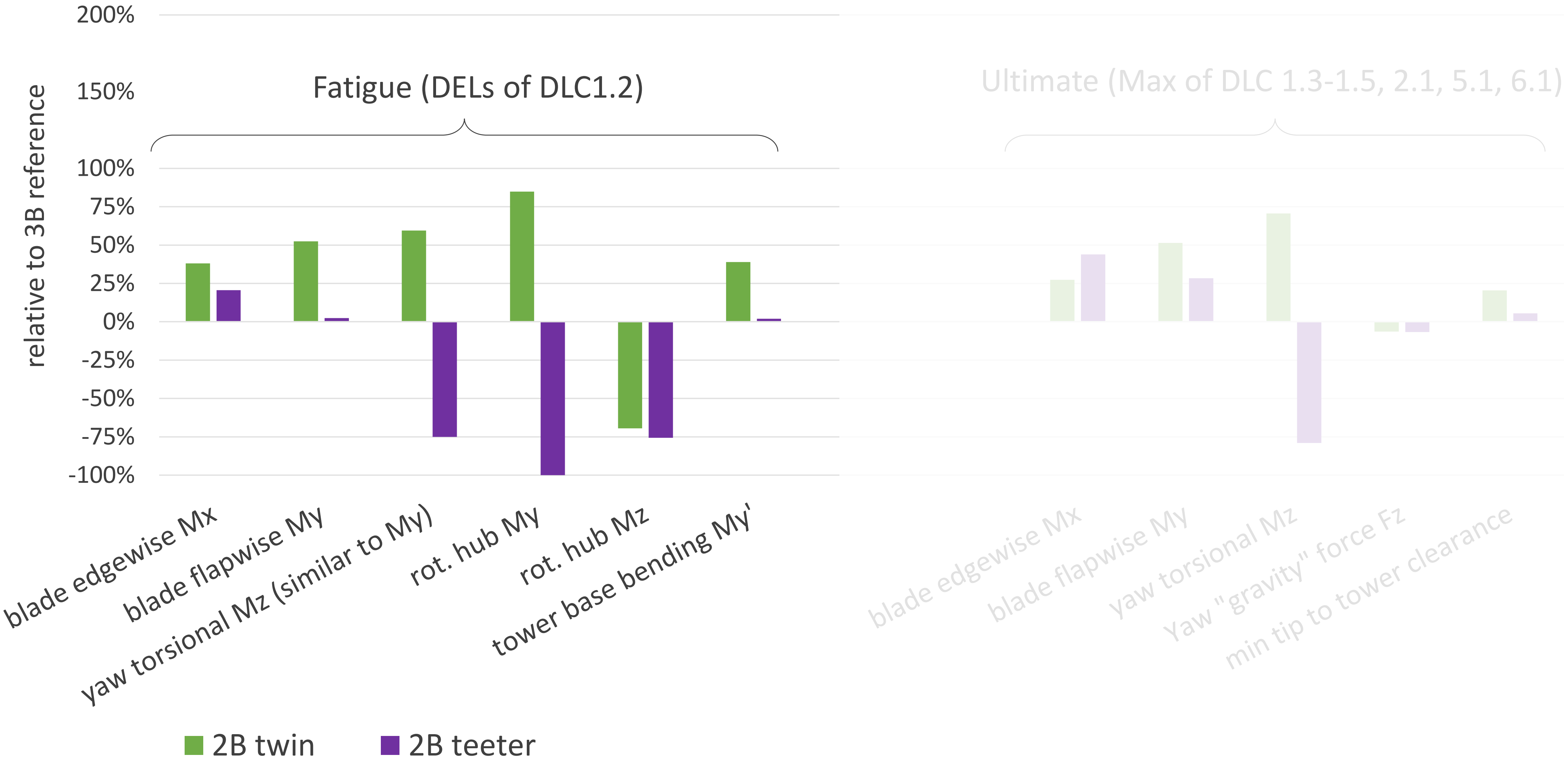

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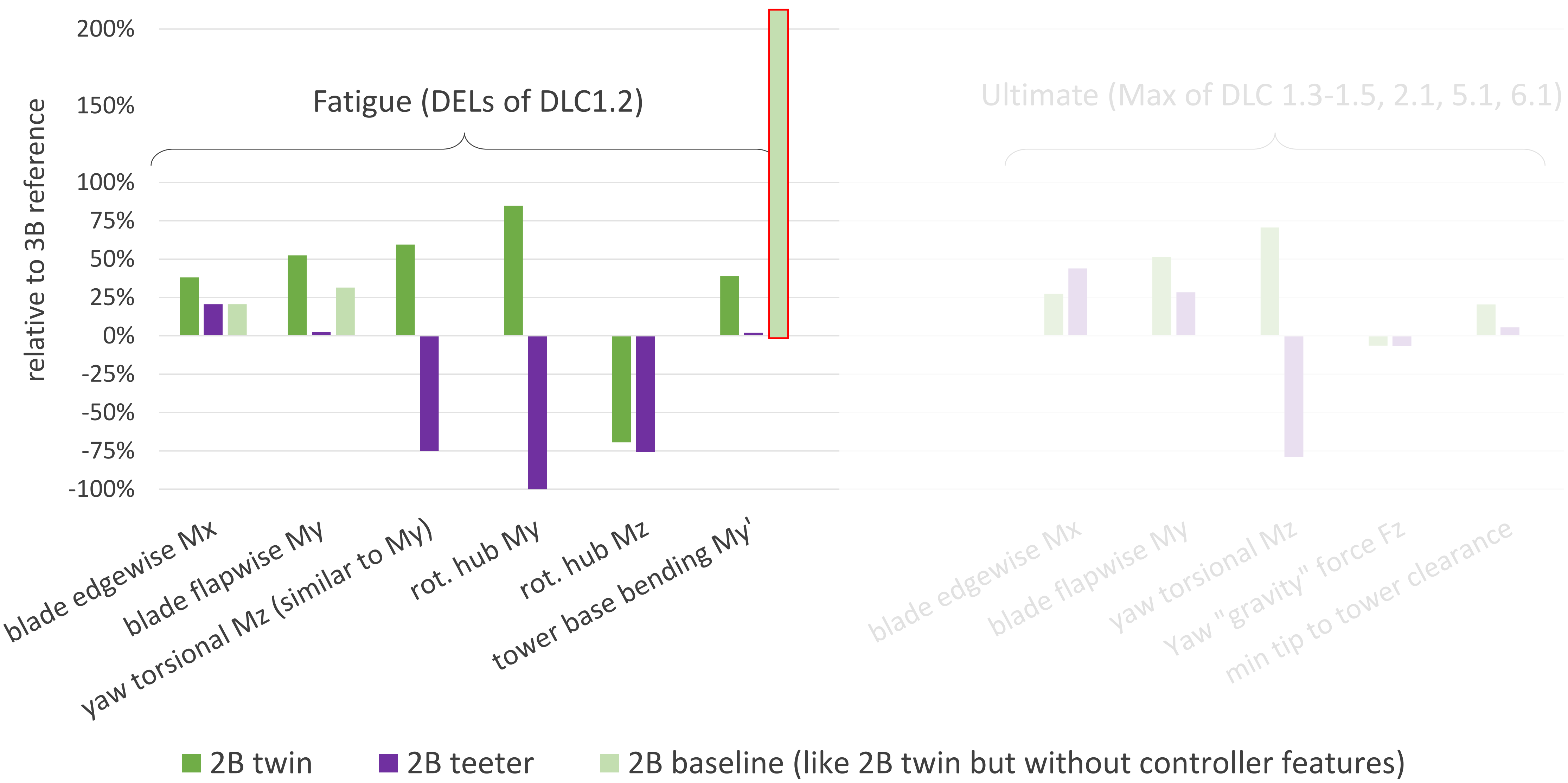
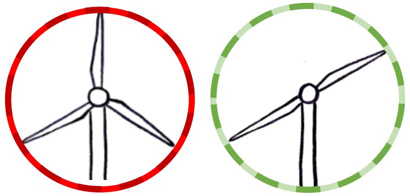
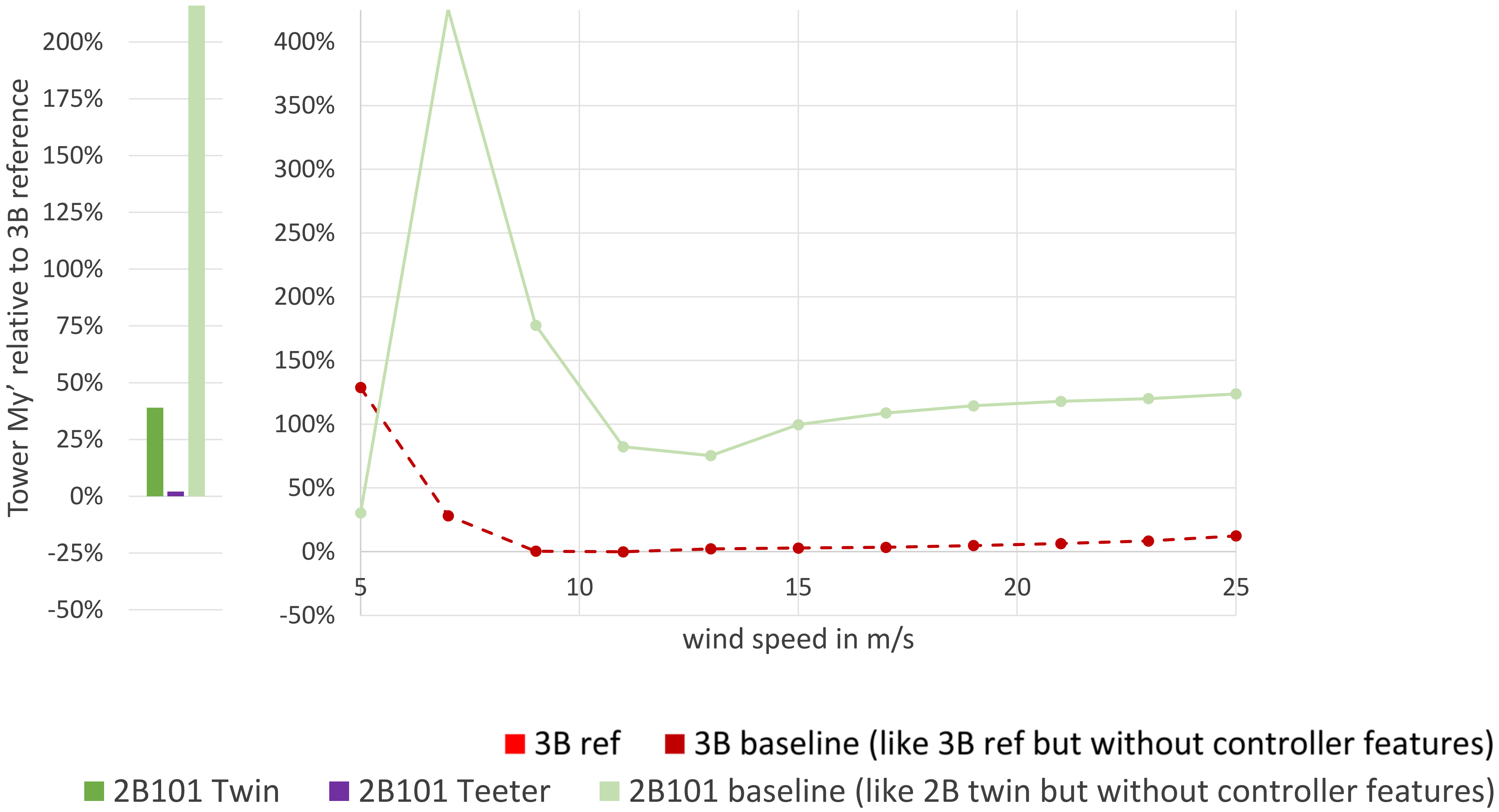


1) Load difference: Tower fatigue 2B vs. 3B in DLC 1.2





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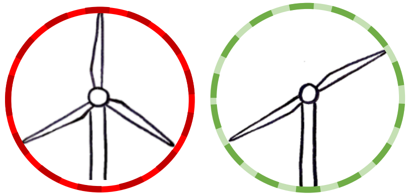

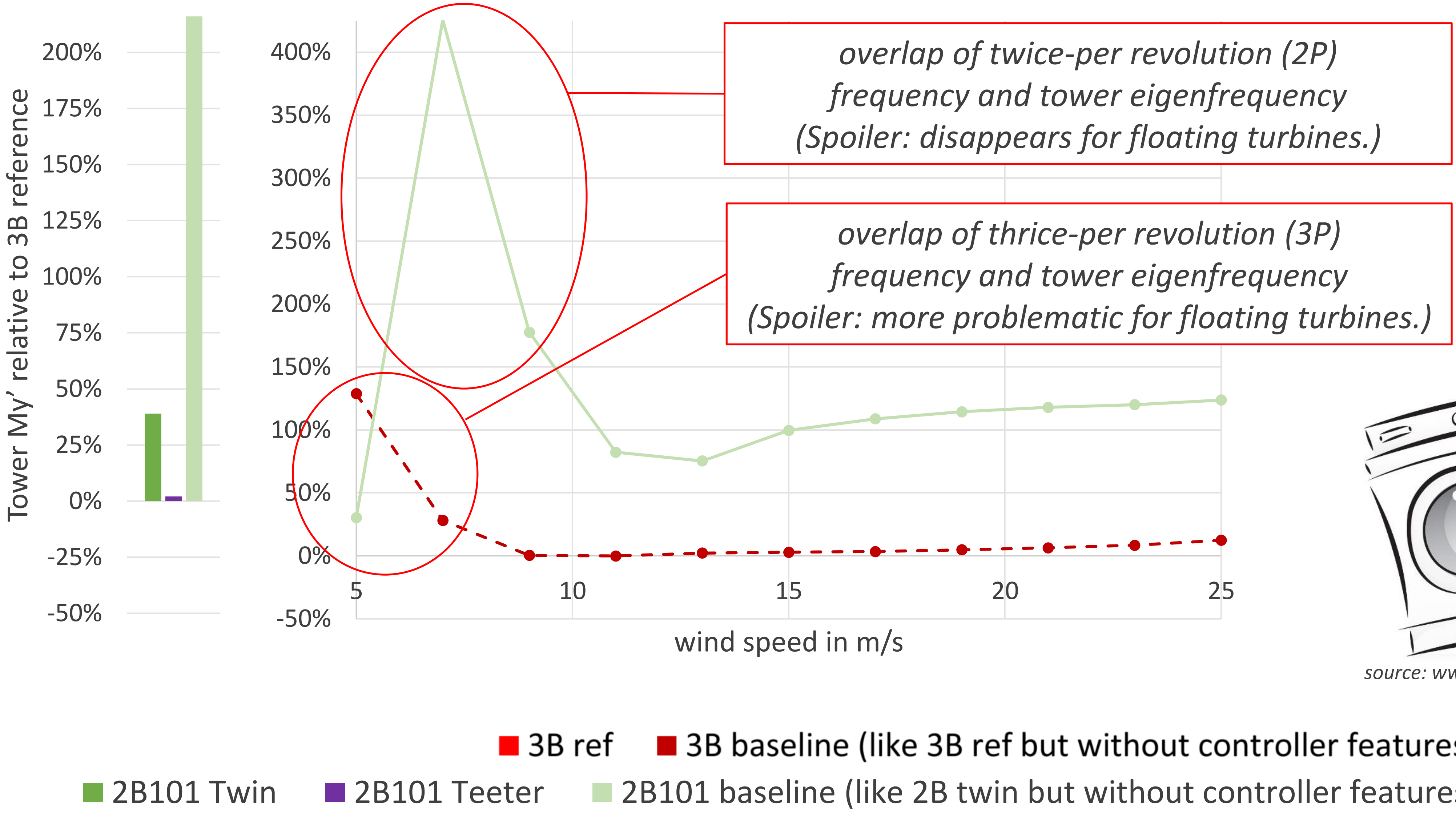

source: www.hausjournal.net

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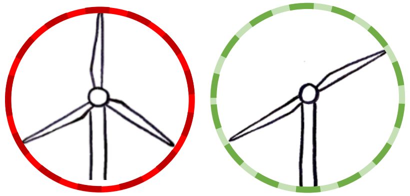

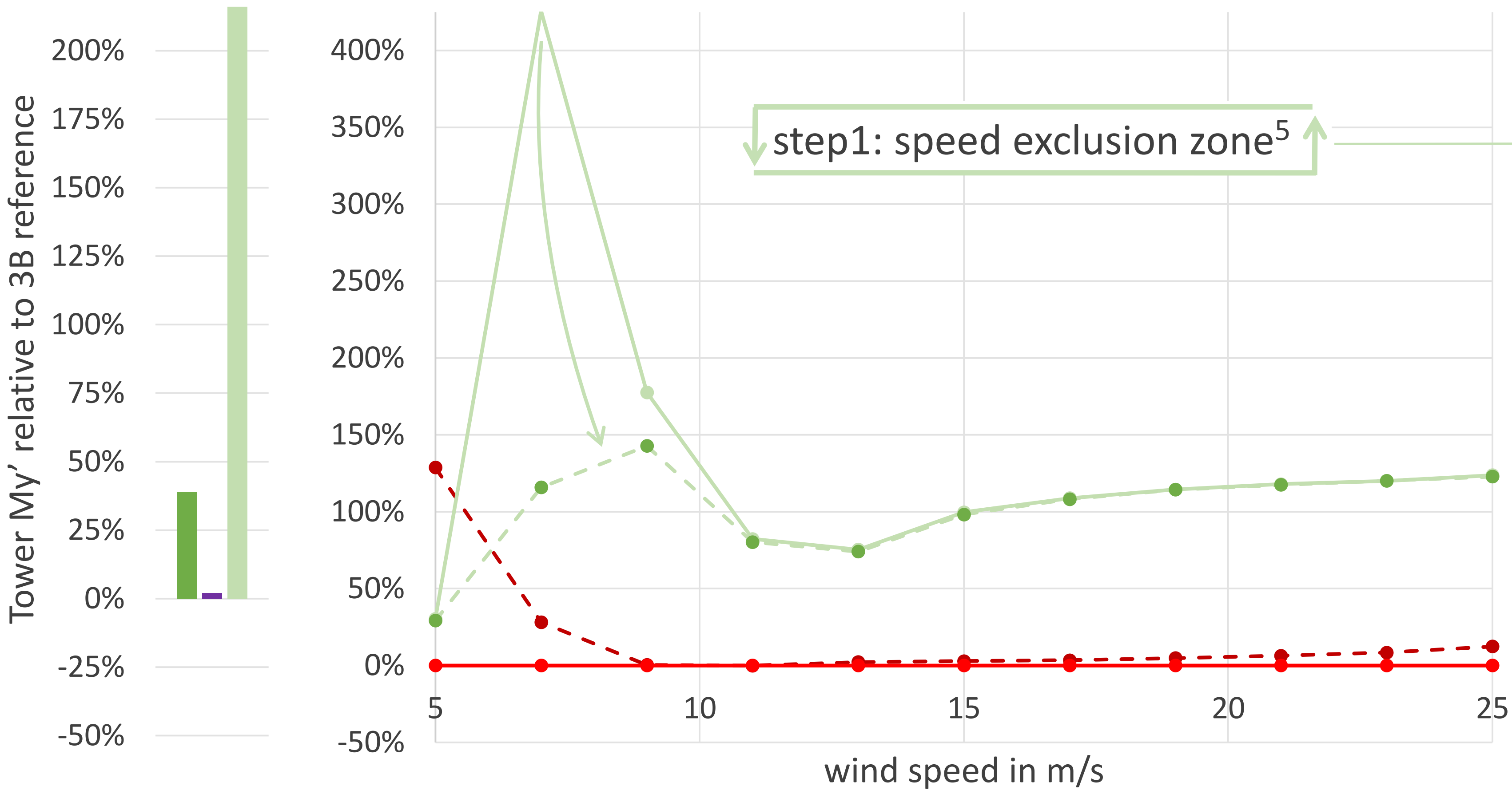

Avoid eigenfrequency excitation

-> causes power reduction of
0.17% for 2B and
0.03% for 3B

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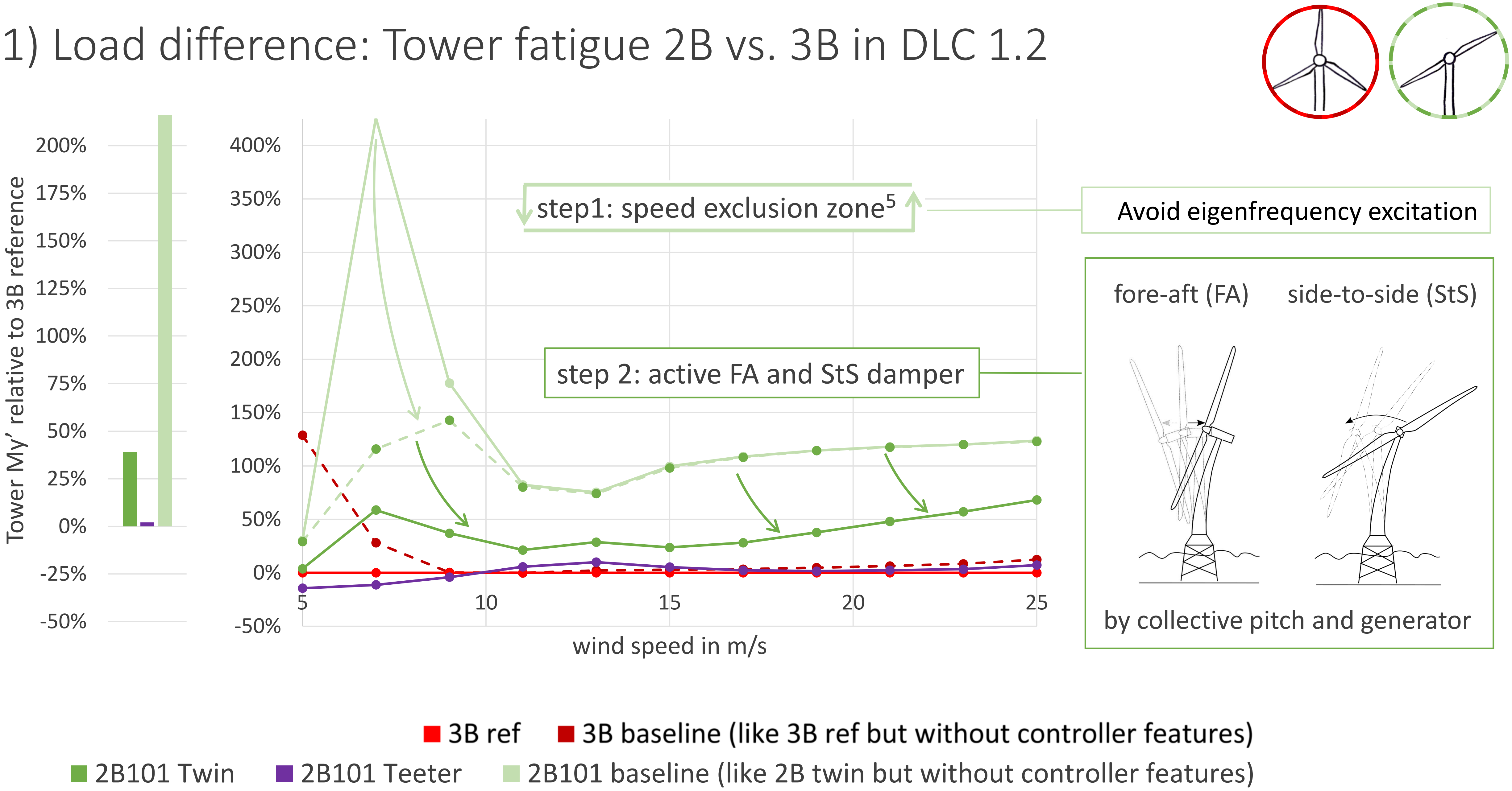

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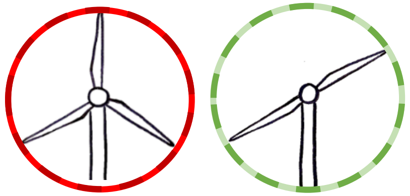
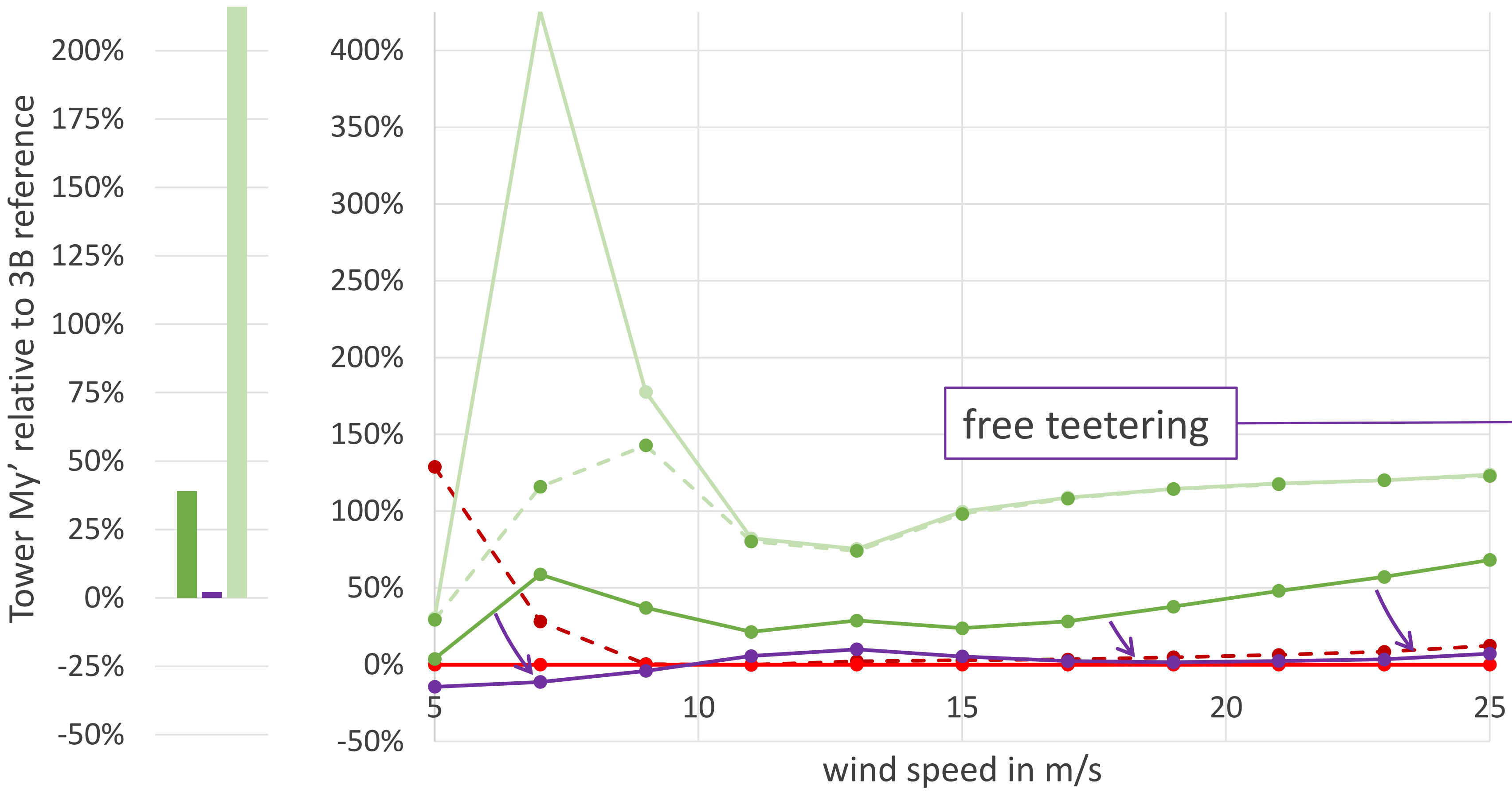
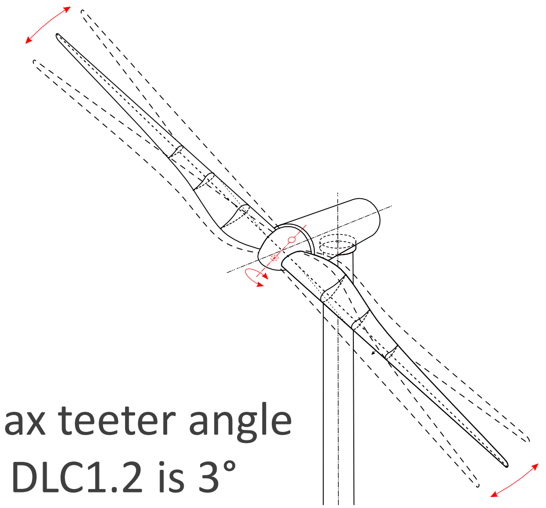
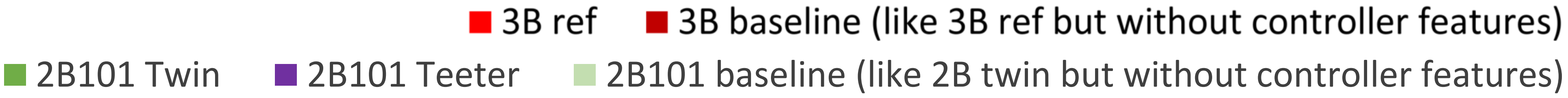


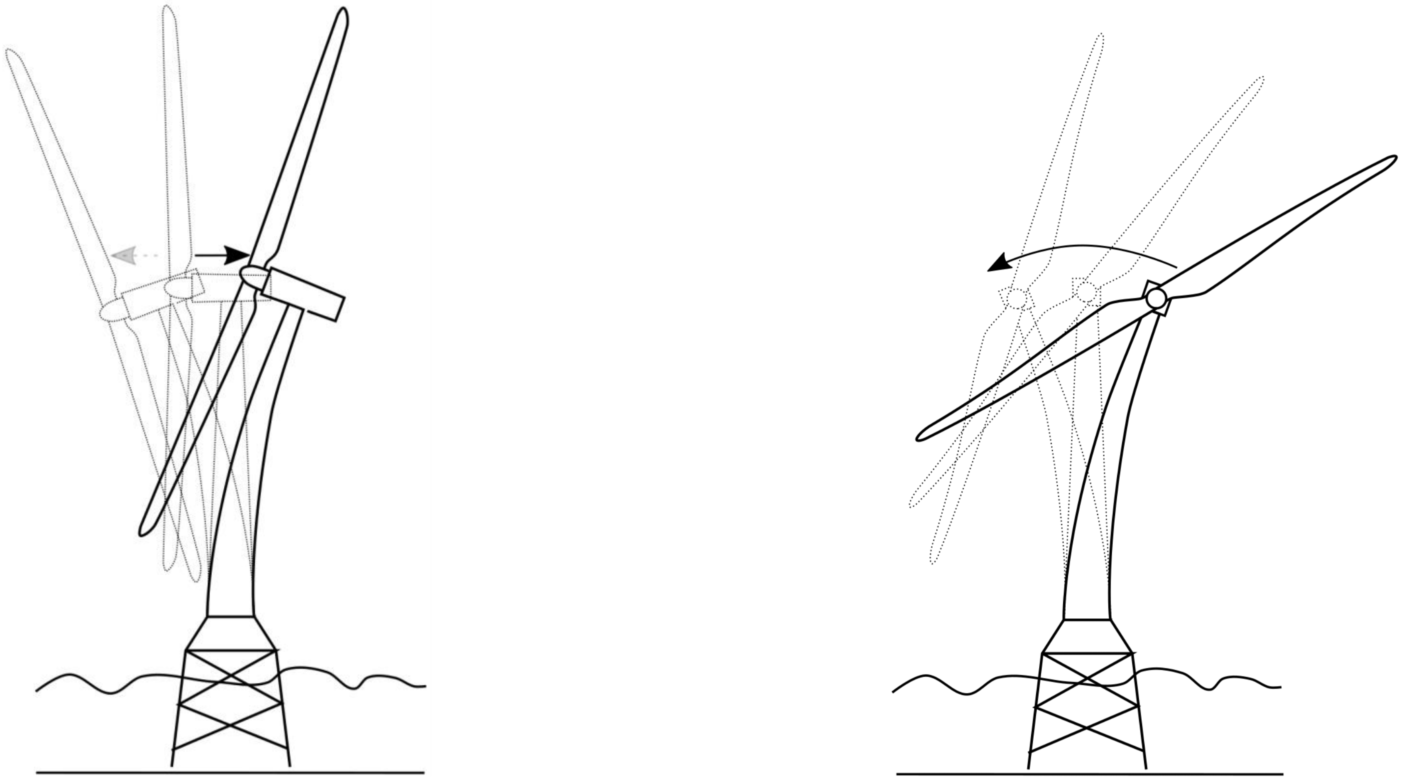




- Max teeter angle in DLC1.2 is 3°
- after 3° pitch-teeter-coupling factor of 2 for extreme loads

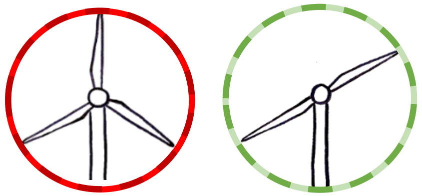


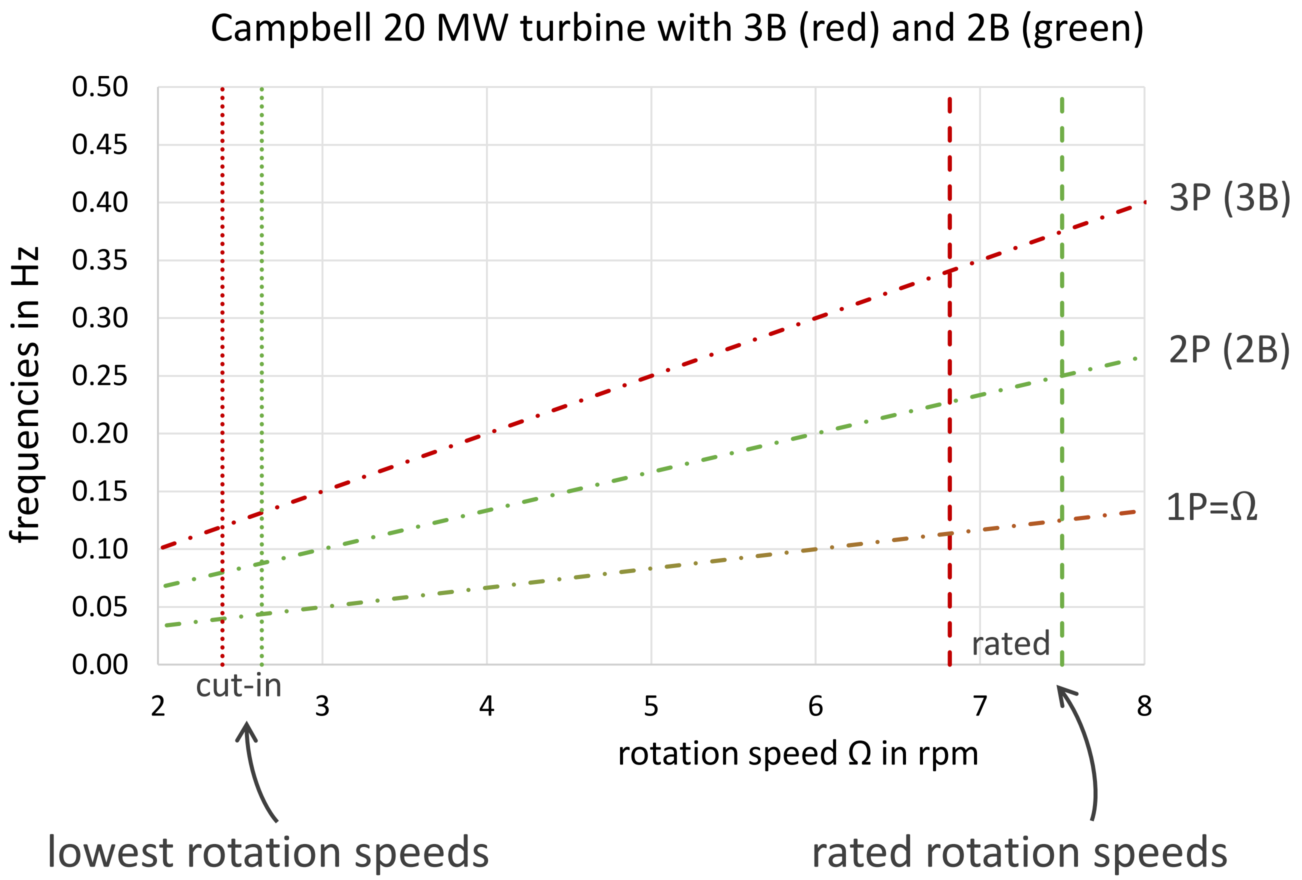
DLC 1.2 with 6 seeds each 0°, +-8° yaw error and Rayleigh distribution with 11.4 m/s mean wind speed.



Campbell diagram

2) Campbell diagram – focus on first tower eigenfrequencies





1P, 2P and 3P => once, twice or thrice per revolution

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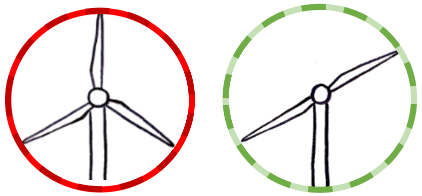
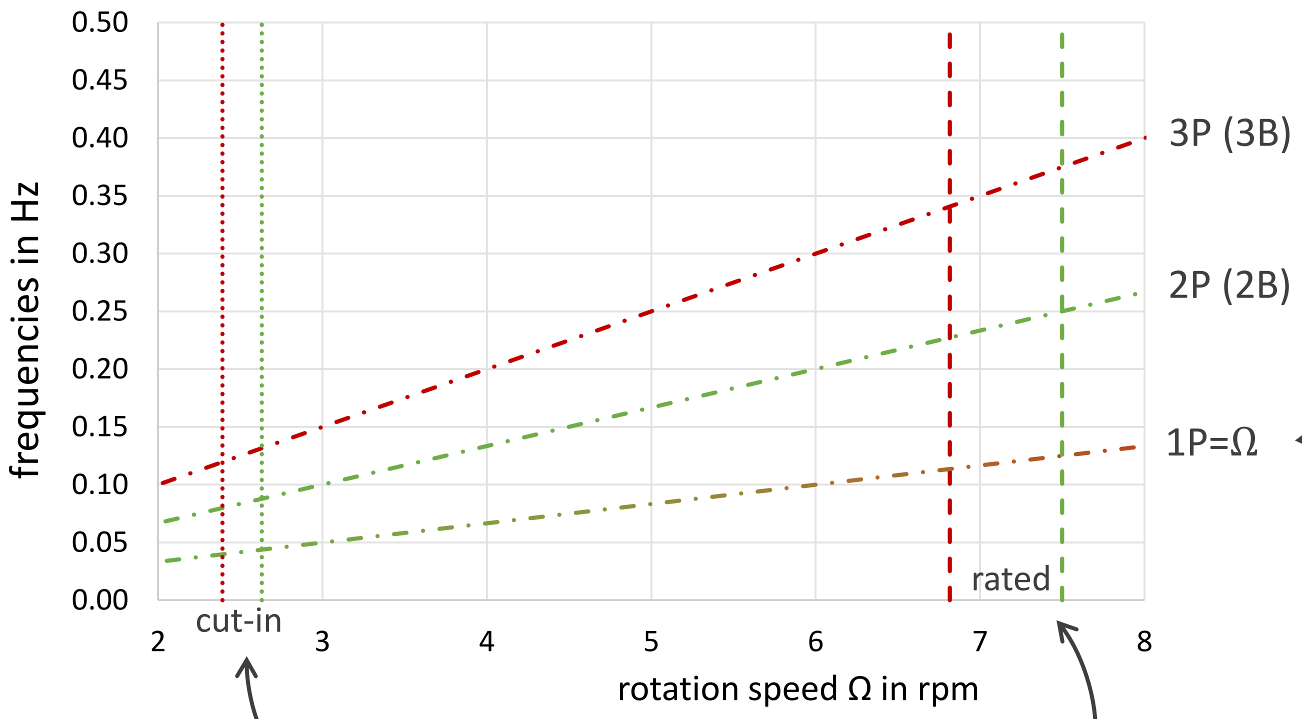
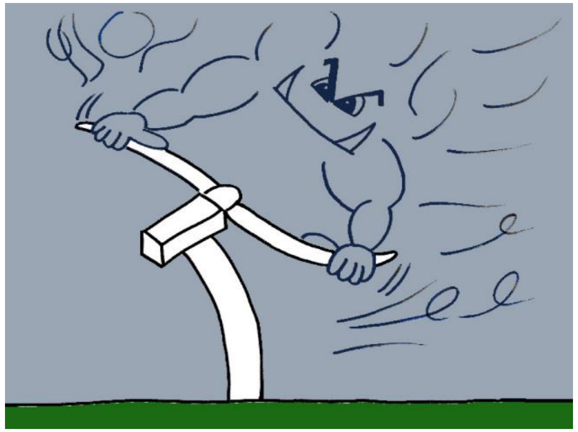


Campbell 20 MW turbine with 3B (red) and 2B (green)



aerodynamic "excitation"



e.g. imbalance

source: www.hausjournal.net

lowest rotation speeds

rated rotation speeds

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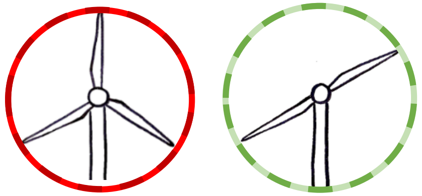

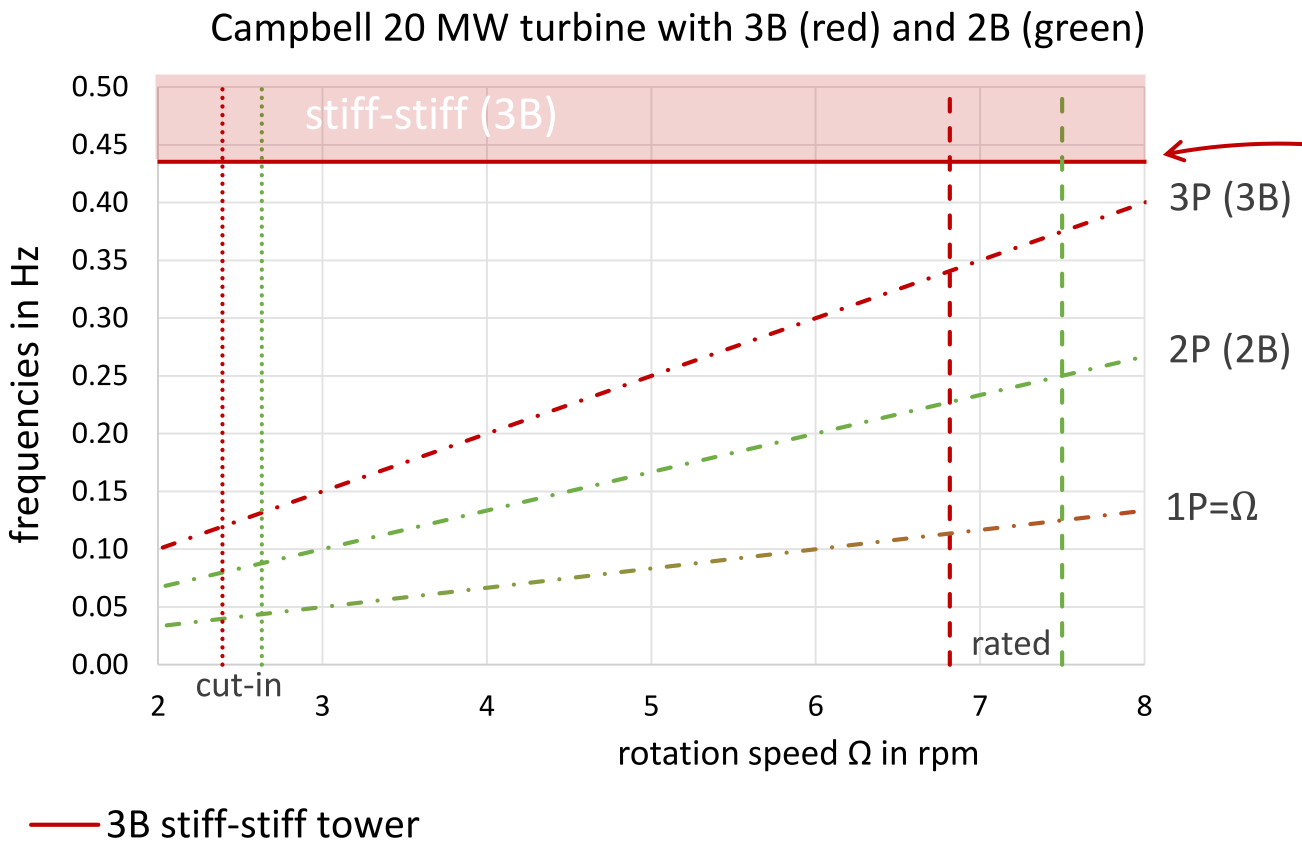

stiff-stiff tower design (standard for floating?):

- tower frequency ***above*** 2P or 3P

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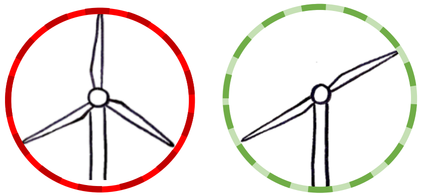
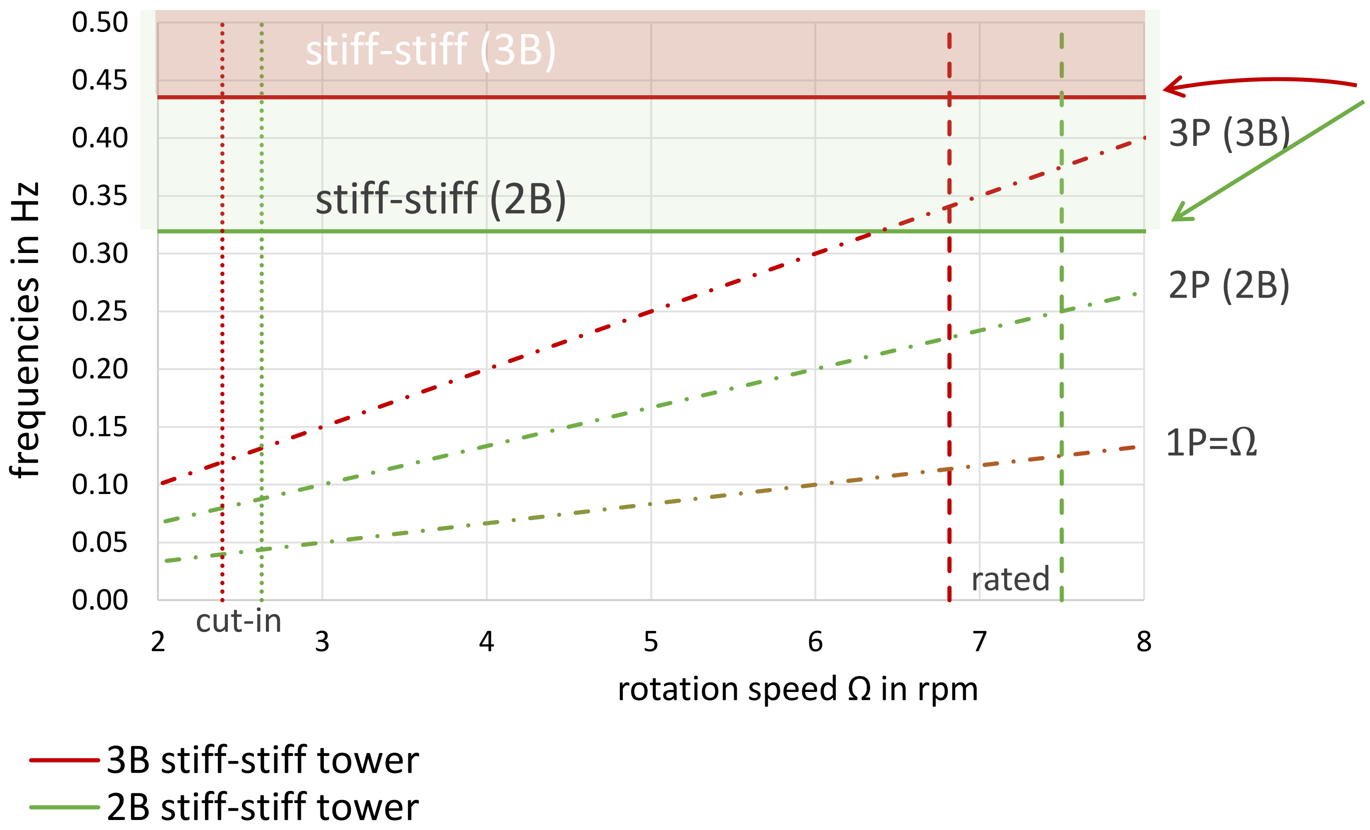


Campbell 20 MW turbine with 3B (red) and 2B (green)



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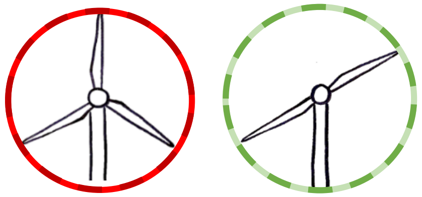

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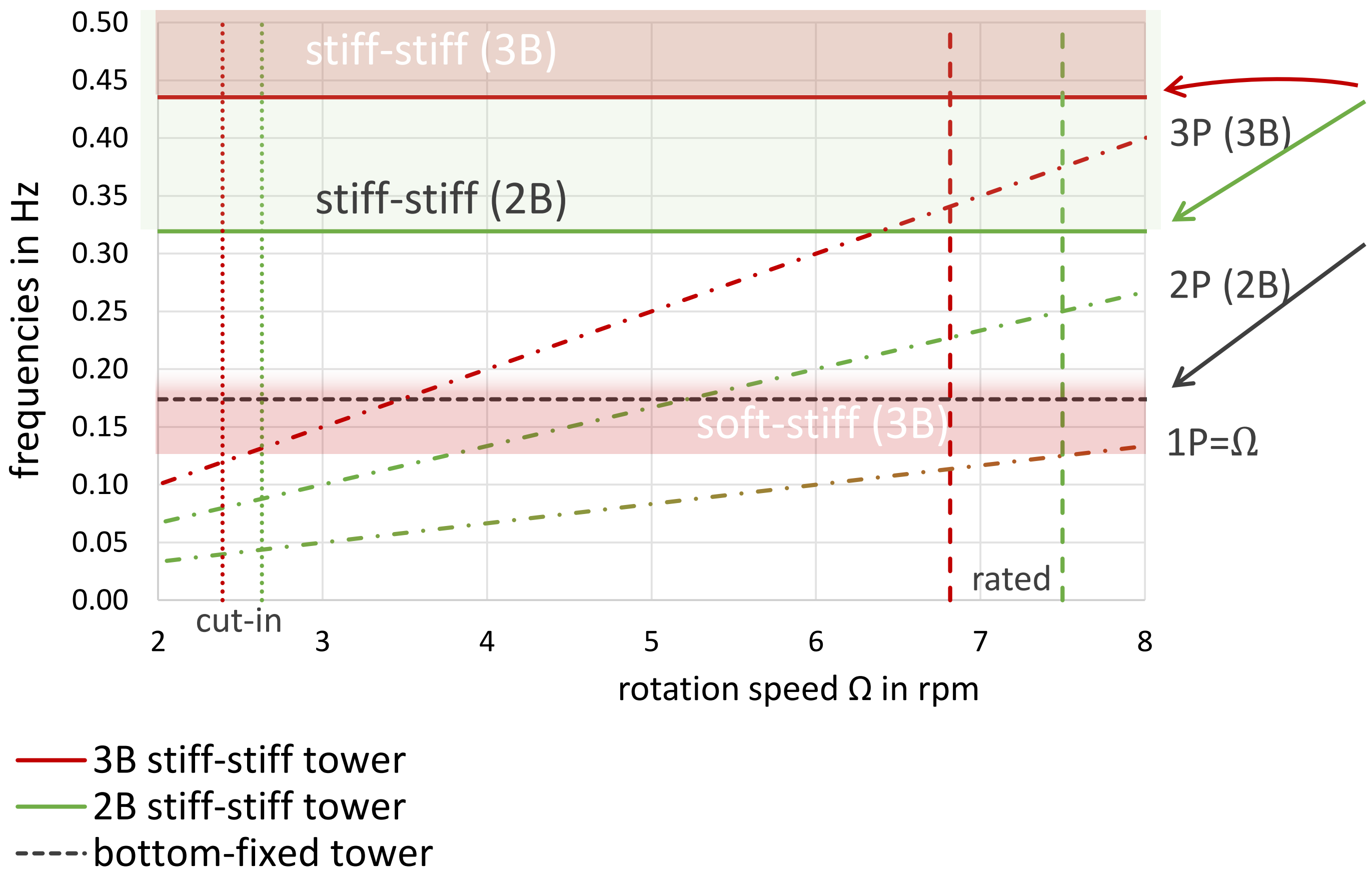

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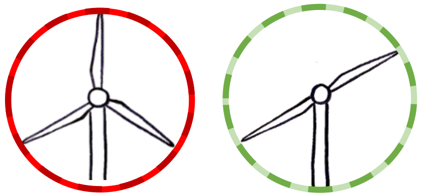

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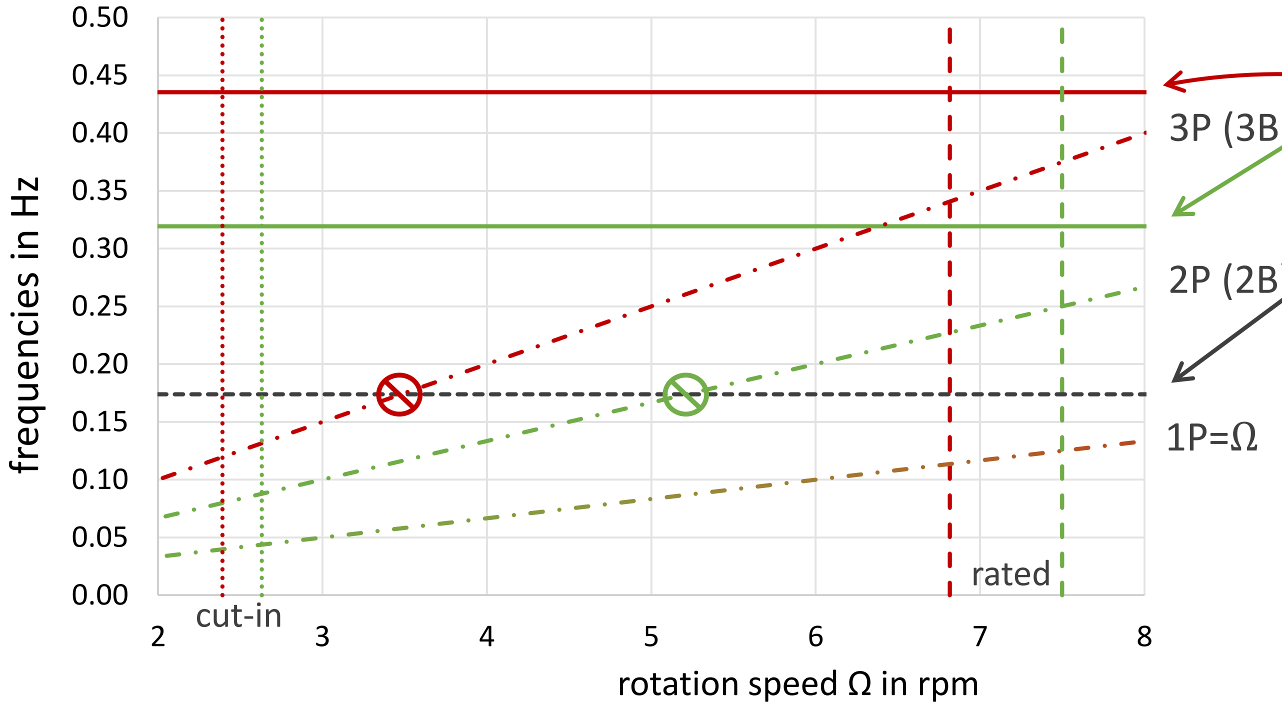

——3B stiff-stiff tower
——2B stiff-stiff tower
----- bottom-fixed tower

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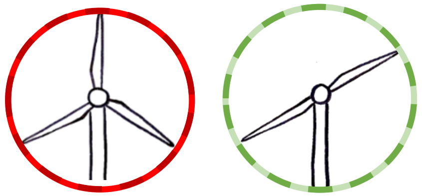

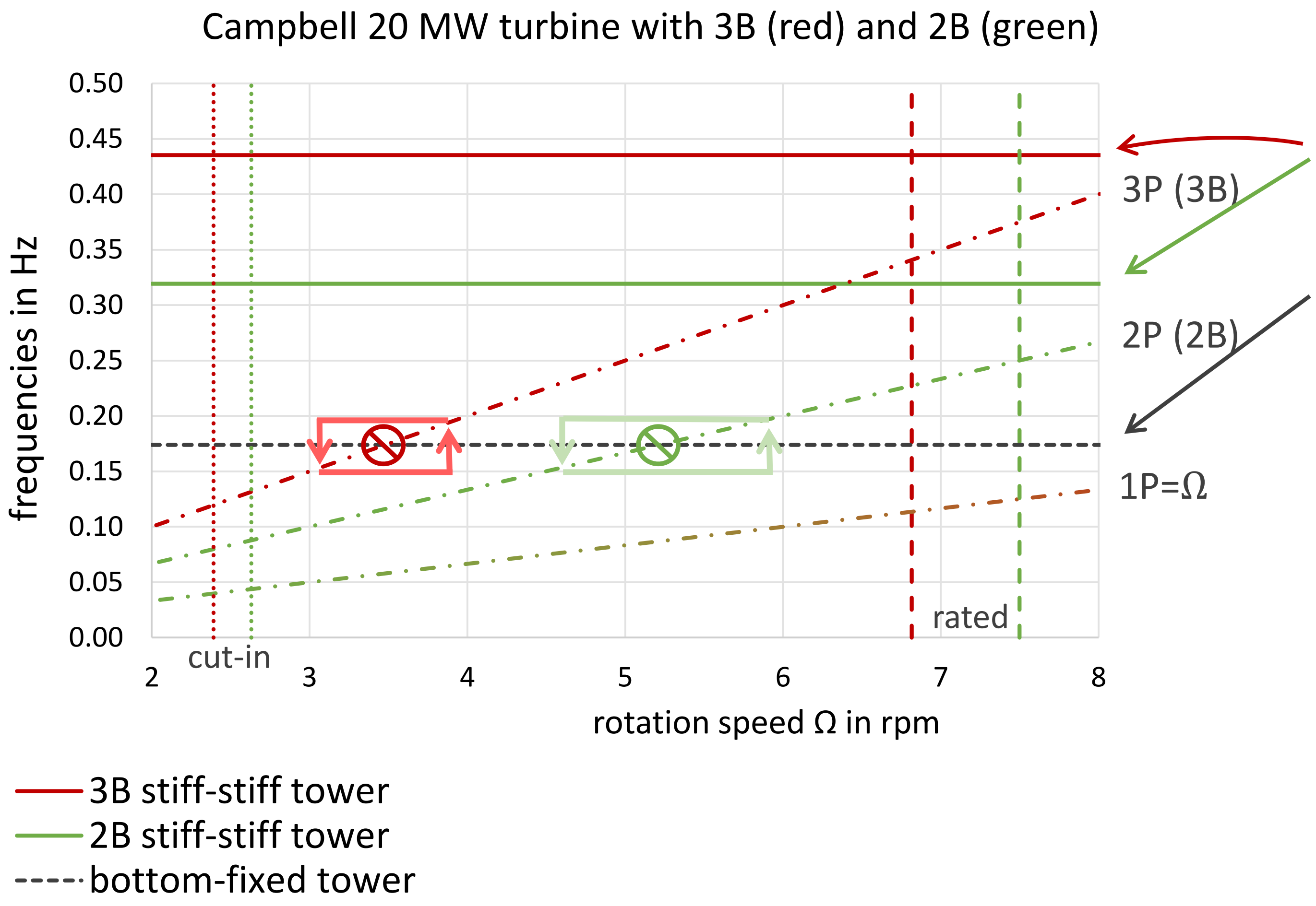

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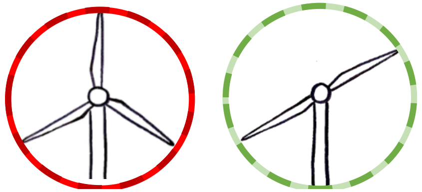
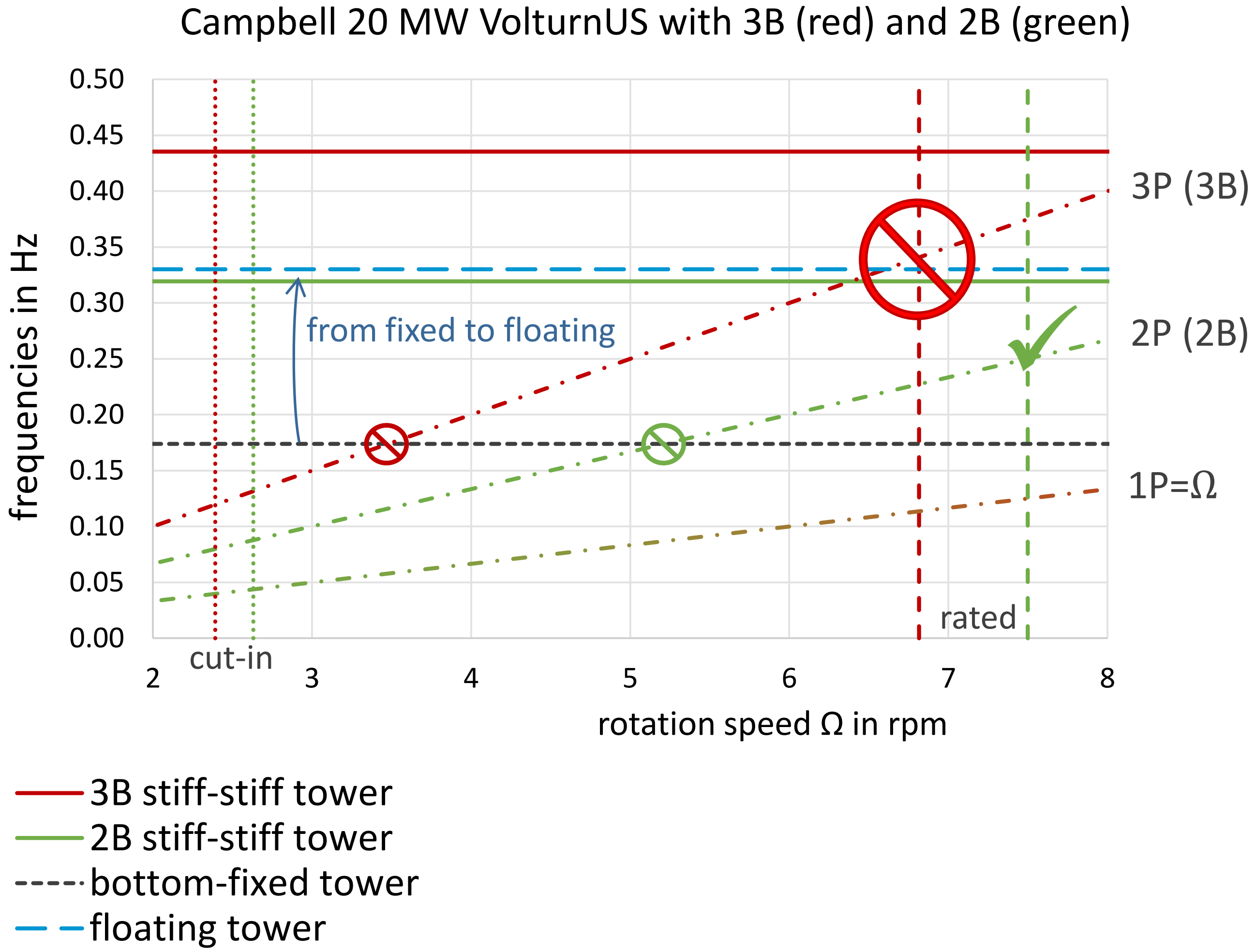
➢ *Very little space between 1P and 2P* thus high tower fatigue of two-bladed turbine (with classical bottom-fixed tower).

➢ „adjust" tower eigenfrequency is extremely expensive. (speed exclusion zone is cheaper.)

1P, 2P and 3P => once, twice or thrice per revolution

2) Tower eigenfrequency – big two-bladed turbines issue or advantage?





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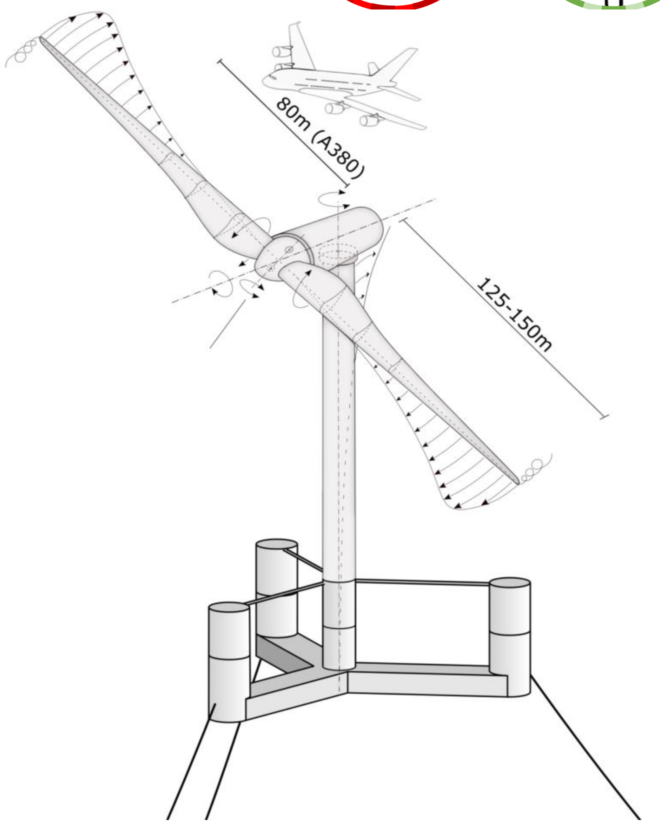

- tower eigenfrequency increases vastly for floating turbines
- problematic for three-bladed turbines due to high 3P-frequency

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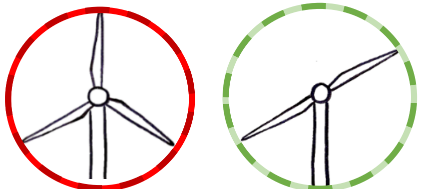

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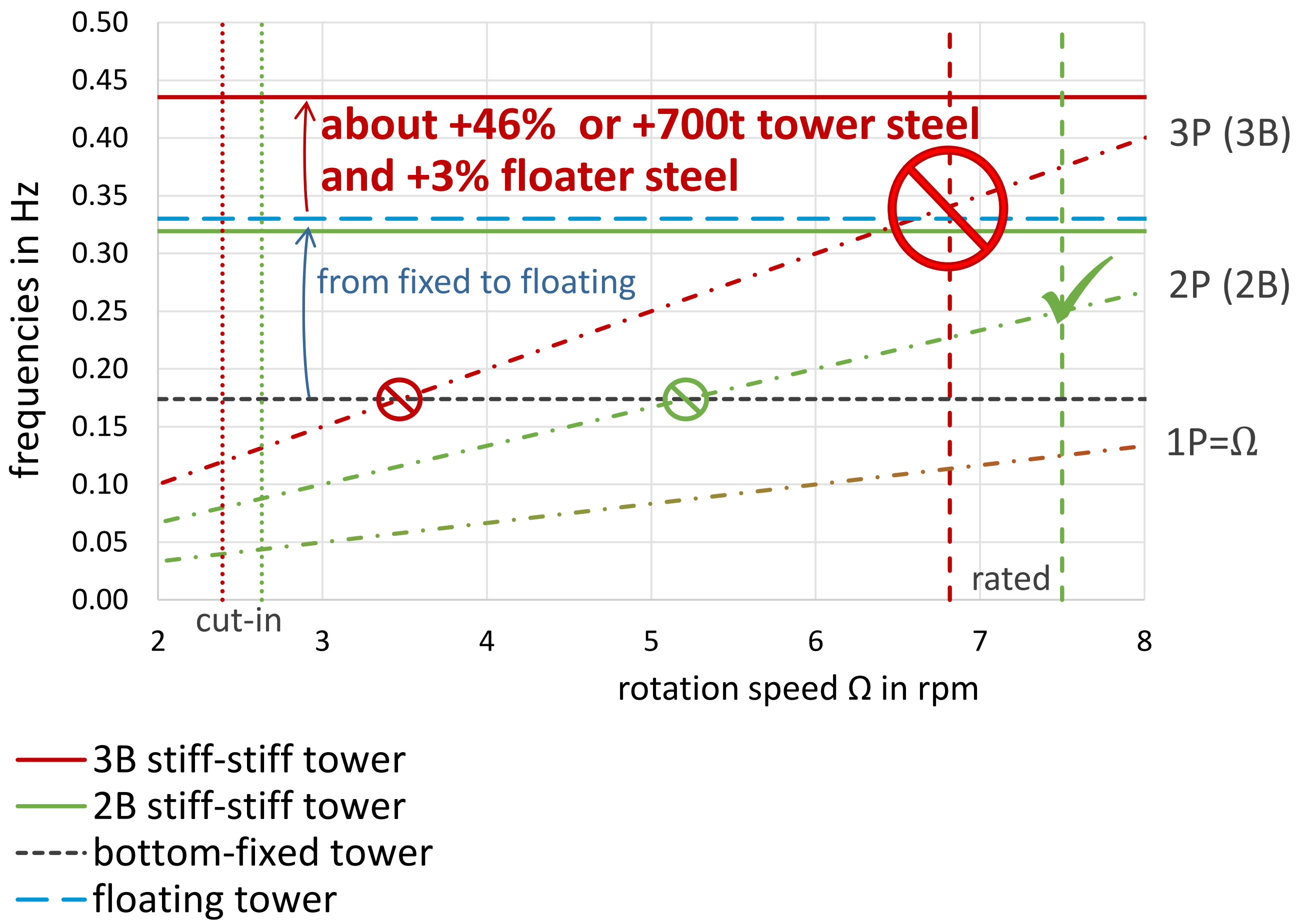

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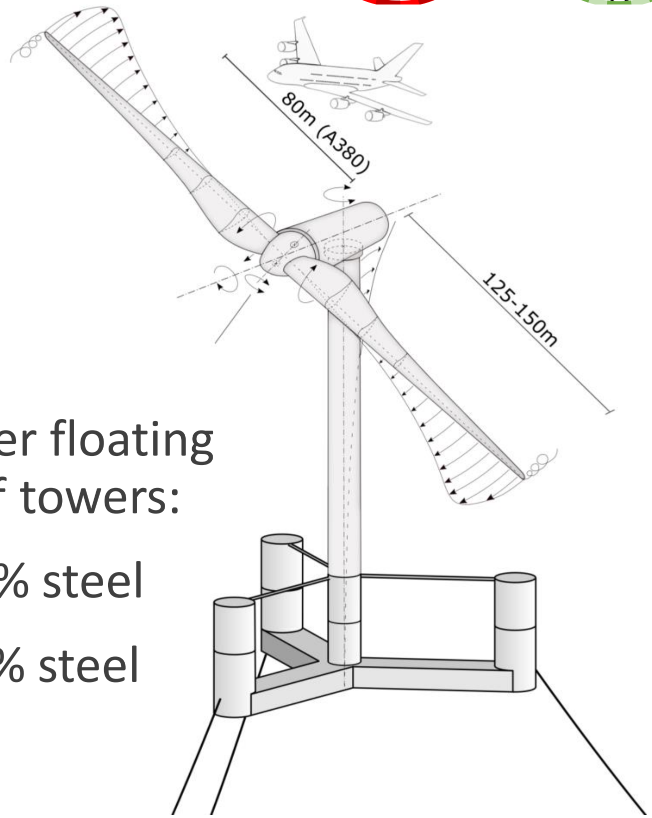


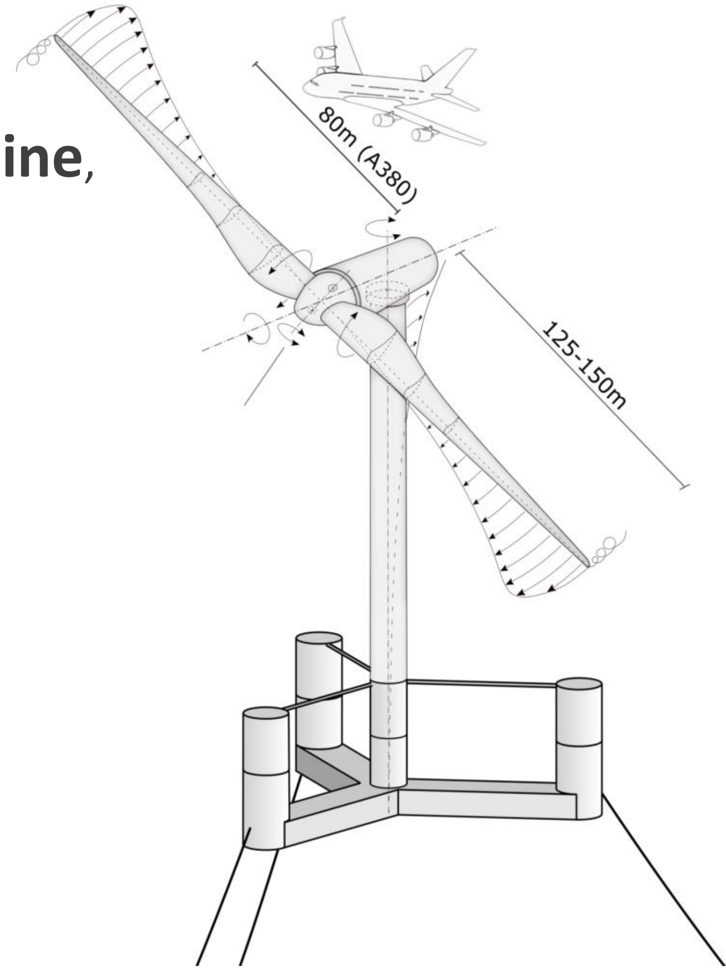
Compared to other floating turbine's stiff-stiff towers:

- NREL with +55% steel
- EDF with +72% steel

- tower eigenfrequency increases vastly for floating turbines
- problematic for three-bladed turbines due to high 3P-frequency

4) Summary

- **Bottom-fixed: Tower fatigue issues for a two-bladed 20MW turbine**, due to naturally poor soft-stiff tower design options.
- **Floating: Tower fatigue issues for a three-bladed 20MW turbine.**
  Cost and load advantages for two-bladed towers.
  Severe two-bladed tower loads disappear.



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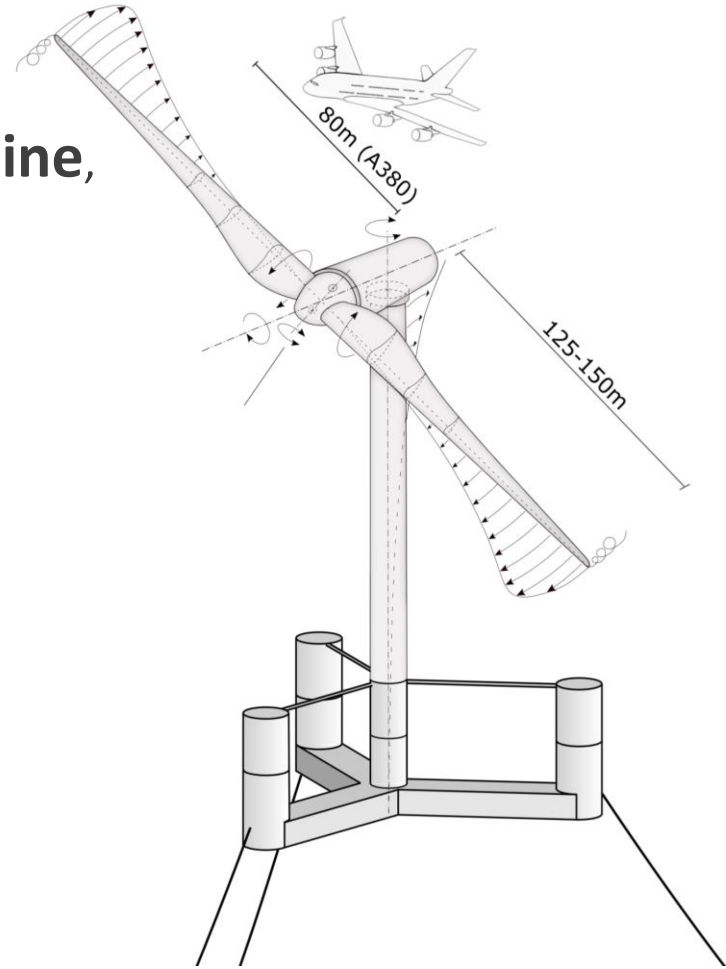
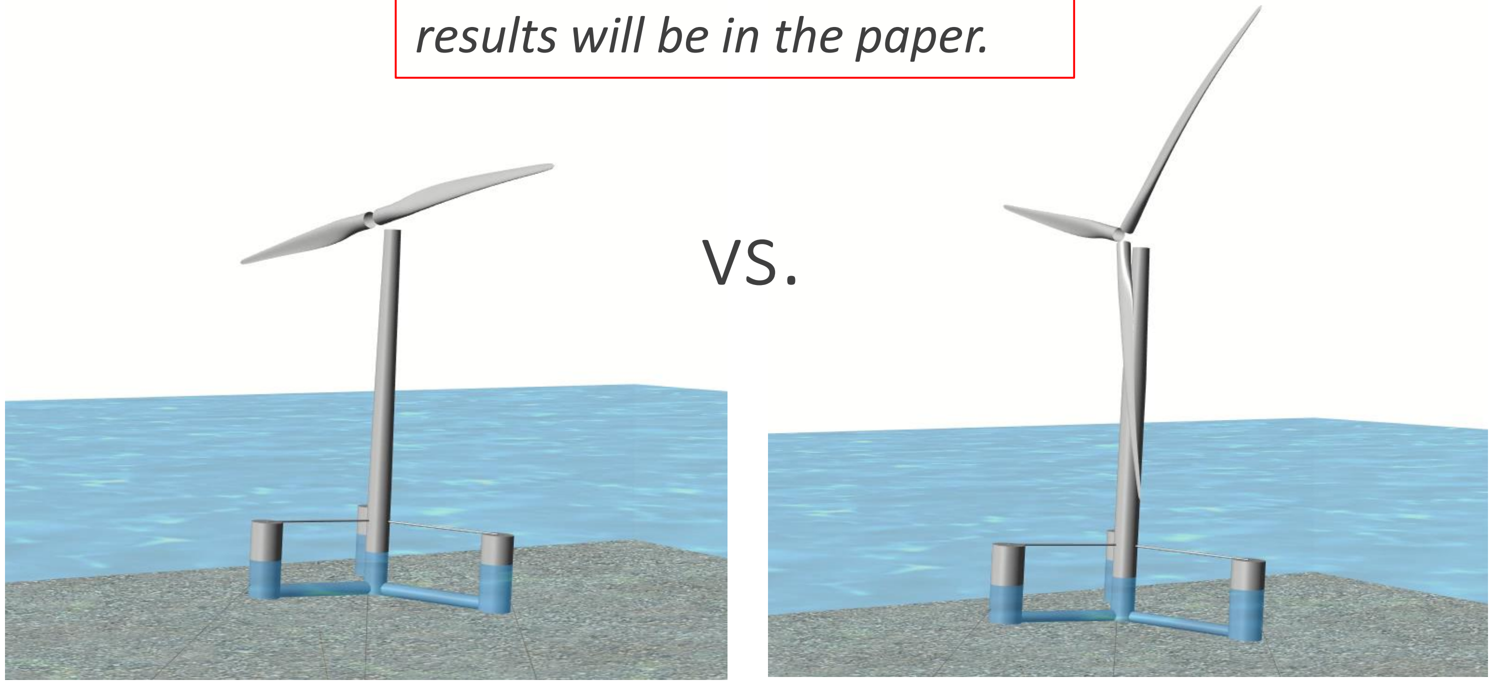


Further two-bladed advantages:

- **Teetering motion (and teeter-issues) decrease with turbine sizes**
- **Two-bladed turbine‘s blades are easier to upscale**
  (larger tip tower clearance and higher strength to weight ratio)
- **Less mass in the rotor and generator thus less rotor-nacelle inertia**
- **Further cost reductions in the whole life-cycle**
  (one blade, bearing and actuator less to manufacture, transport, erect, maintain, decommission + lighter tower and floater)

Thank you for your time

More details on an objective floater design and simulation results will be in the paper.



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and

EnBW

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Research Associate

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Berliner Tor 21 / 20099 Hamburg

Own references

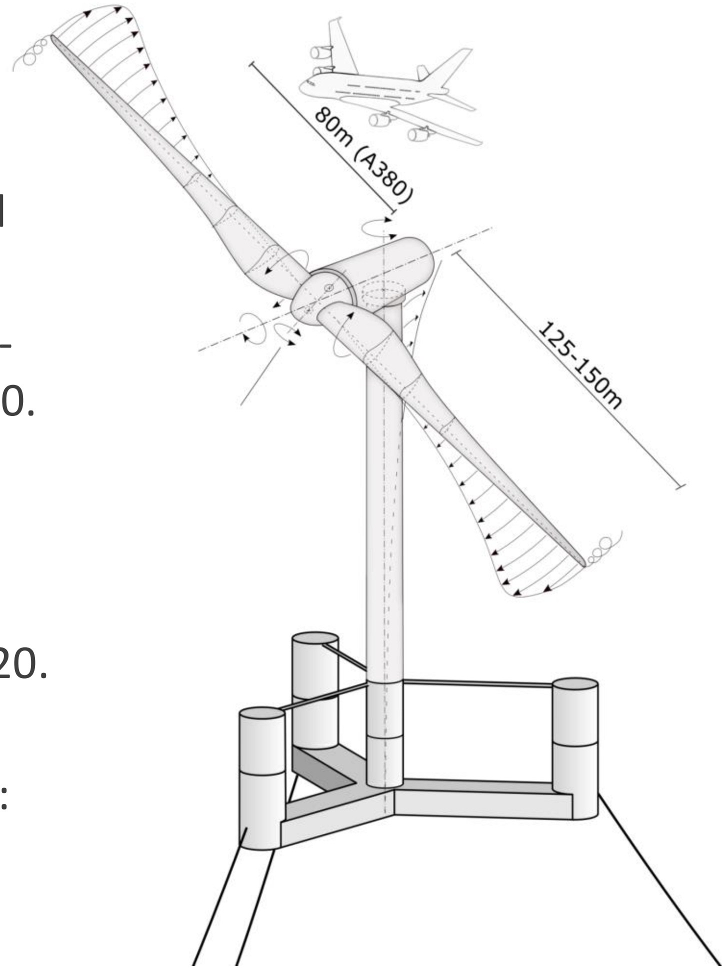
[1] Anstock F., Schütt M., and Schorbach V. A new approach for comparability of two- and three-bladed 20 MW offshore wind turbines. JoP, 2019.

[2] Schütt M., Anstock F., and Schorbach V. Progressive structural scaling of a 20 MW two-bladed offshore wind turbine rotor blade examined by finite element analyses.JoP,2020.

[3] Schütt M., Anstock F., and Schorbach V. A procedure to redesign a comparable blade structure of a two-bladed turbine based on a three-bladed reference. JoP, 2021.

[4] Anstock F. and Schorbach V., A control cost criterion for controller tuning of two- and three-bladed 20MW offshore wind turbines, Journal of Physics: Conference Series, 2020.

[5] Anstock F. and Schorbach V. The effect of a speed exclusion zone and active tower dampers on an upwind fixed-hub two-bladed 20 MW wind turbine. Journal of Physics: Conference Series, 2021.



OBJECTIVE (pre-)design steps for a two- and three-bladed floater

$$C_{55} = \sum -z_i m_i g + M_{\mathrm{wtrpln}} + z_{\mathrm{COB}} m_{\mathrm{FOWT}} g + C_{\mathrm{Lines}}.$$

$$T_{\mathrm{eig},55} \approx \frac{2\pi}{\sqrt{C_{55}/(M_{55} + A_{55})}}.$$

- rated thrust
- boundary conditions
- stability criteria
- RNA + tower masses

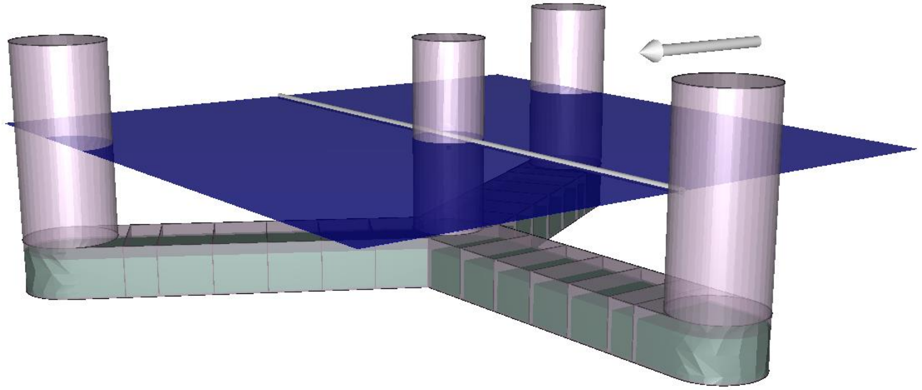
Scale floater dimensions **analytically** (C55, T55)

Check in **HydroD** and get e.g. A55, M55

Check tower frequencies in **Bladed**

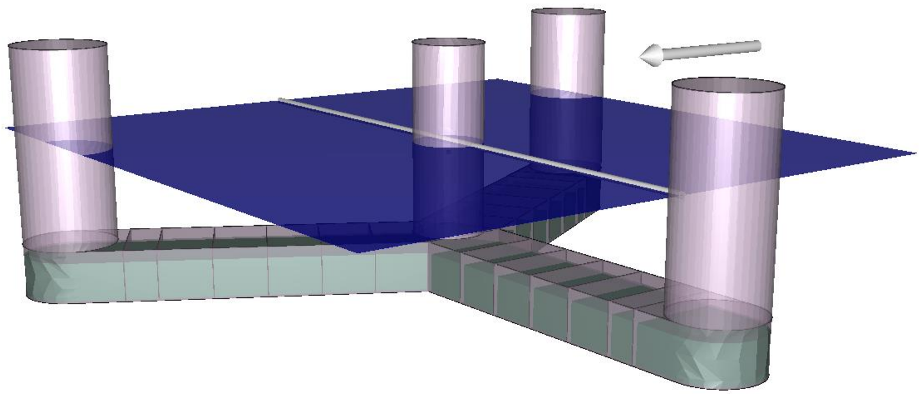
2B vs 3B mass **comparison**
(First result: ~3.4% floater; ~45% tower)

Bladed DLC 1.2 check with slow pitch controller



Necessary boundary conditions

- Freeboard: fixed at 15m ✓
- Center column: fixed at 11m (=20MW tower bottom) ✓
- Outer column Diameter: Linear scaled. ✓
- Pontoon width: Linear scaled. ✓
- Pontoon height: Scaled by complete water ballast filling ✓
- 5° platform heeling angle at mean rated rotor thrust ✓
- Hub height constant → 2B = 30m ground clearance, 3B = 33m ✓ **(for dynamic comparison)**
- Heeling eigenfrequency >= 25s ✓
- Floater drag: Left at 20m ✓
- Steel wall thickness: Linear scaled ✓



Unsure:

- Mooring line diameter: Scaled proportional to floater mass or thrust? **-> to DLC 6.1 max load and uplift**
- Iron ore concrete thickness: **Check if needed**; otherwise linear scaled
- Max. heeling angle? -> advised to be around 15° at ESS ✓

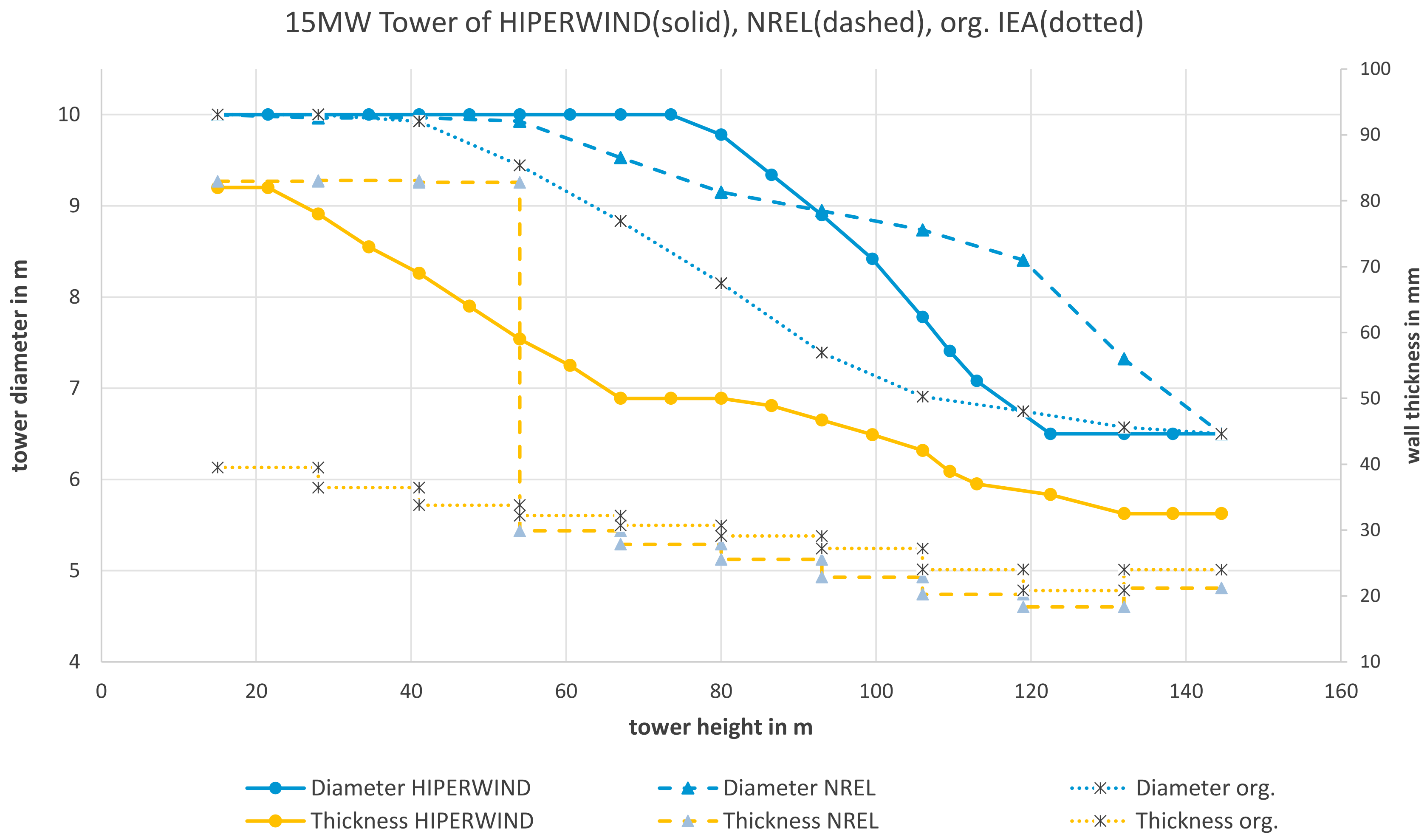
Tower **load** issue

Old (bottom-fixed) tower load approach:

- **3B-tower is driven by 3B-(fatigue) loads**
- **Every increase by 2B-loads have to be compensated by thicker tower walls.**

Now:

- **3B-tower is driven by its eigenfrequency**
- **but 3B tower can withstand huge loads (factor of two for 15 MW VolturnUS vs. Monopile at the base)**



15 MW Tower weights: Original IEA 803.4t, NREL's Volturn 1250t (+55%), HIPERWND 1415t (+72%)

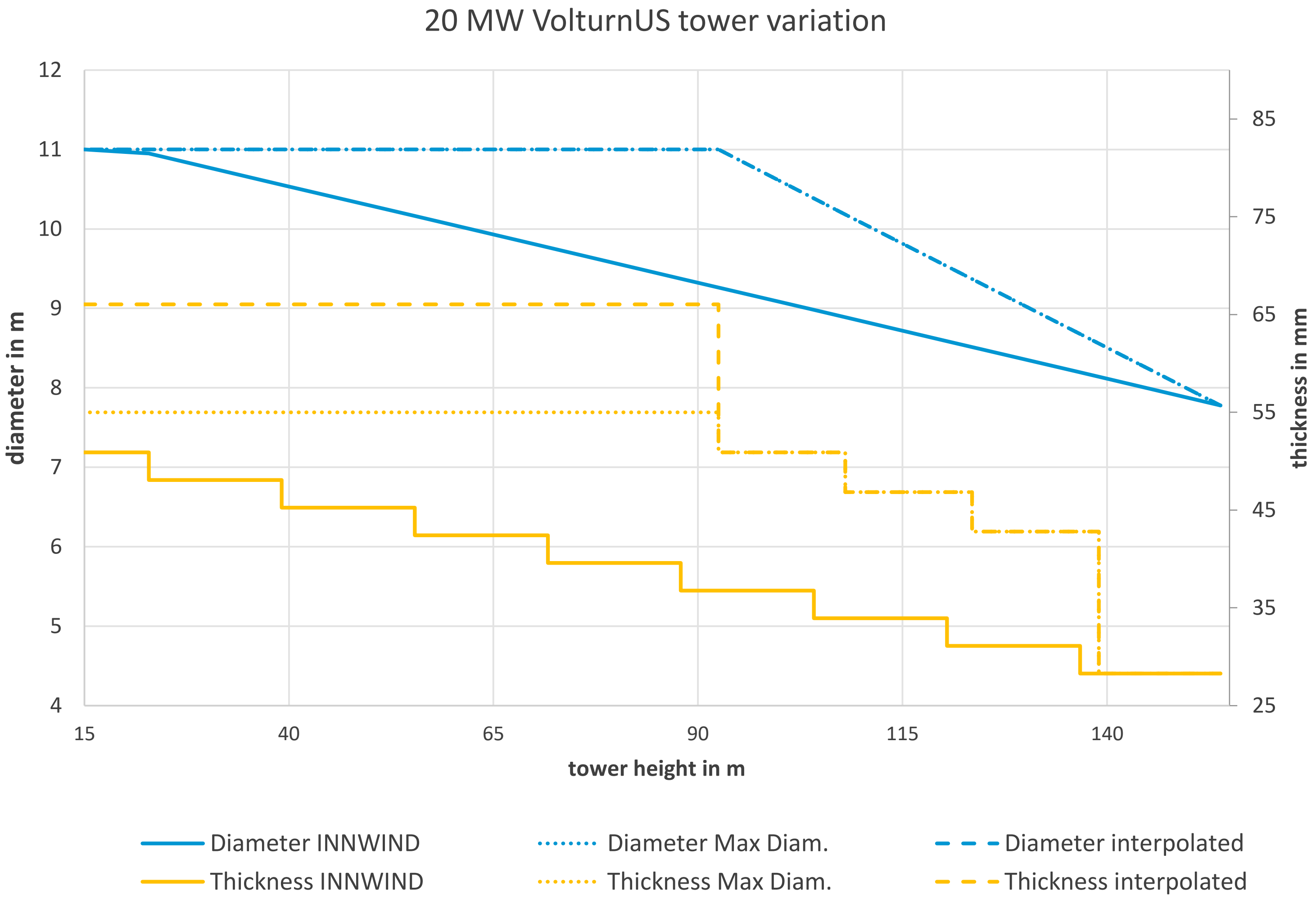
Tower variations for 20 MW

Tower variation with HIPERWIND boundaries:

- **max tower wall inclination of 3 deg**
- **max diameter to thickness ratio of 200**

Results:

- **INNWIND original: 0.33 Hz, 1409t**
- **Max Diameter: 0.42 Hz, 1894t (+38%)**
- ✓ **Max Diam. + interpolated D/t: *0.44 Hz*, 2124t, (+56%) (For 15 MW it had been 72%)**



15 MW Tower weights: Original IEA 803.4t, NREL‘s Volturn 1250t (+55%), HIPERWND 1415t (+72%)

Turbine data: X-Rotors' three-bladed and two-bladed turbines

	20 MW 3B Reference (pitch-controlled, fixed hub)	20 MW 2B Twin (pitch-controlled, fixed hub)	20 MW 2B Teeter (pitch-controlled, teetering hub)
Rotor diameter	252.2 m	257.4 m	257.4 m
Rated tip speed	90 m/s	101 m/s	101 m/s
Rated wind speed	11.4 m/s	11.4 m/s	11.4 m/s
Rated rotor speed	6.82 rpm	7.49 rpm	7.49 rpm
Controller concept	Variable-speed PI-controller, StS- and FA-tower damper	Variable-speed PI-controller, StS- and FA-tower damper	Variable-speed PI-controller, StS- and FA-tower damper
Blade mass	117.9 t	164.4 t	138.3 t
Total blade mass Σ	353.7 t	328.8 t (-7 %)	276.6 t (-21.8%)
Rotor mass (incl. hub)	636.2 t	611.2 t	559.1 t
Hub height	167.9 m	167.9 m	167.9 m
Tower height	163.14 m	163.14 m	163.14 m
Tower mass	1353.6 t	2355.3 t (+74 %)	1371.2 t (+1.3%)
1st tower eigenfrequency	0.166 Hz	0.168 Hz	0.17 Hz
Drive train concept	Direct-Drive	Direct-Drive	Direct-Drive
Nacelle mass	1098.0 t	1050.2 t	1050.2 t

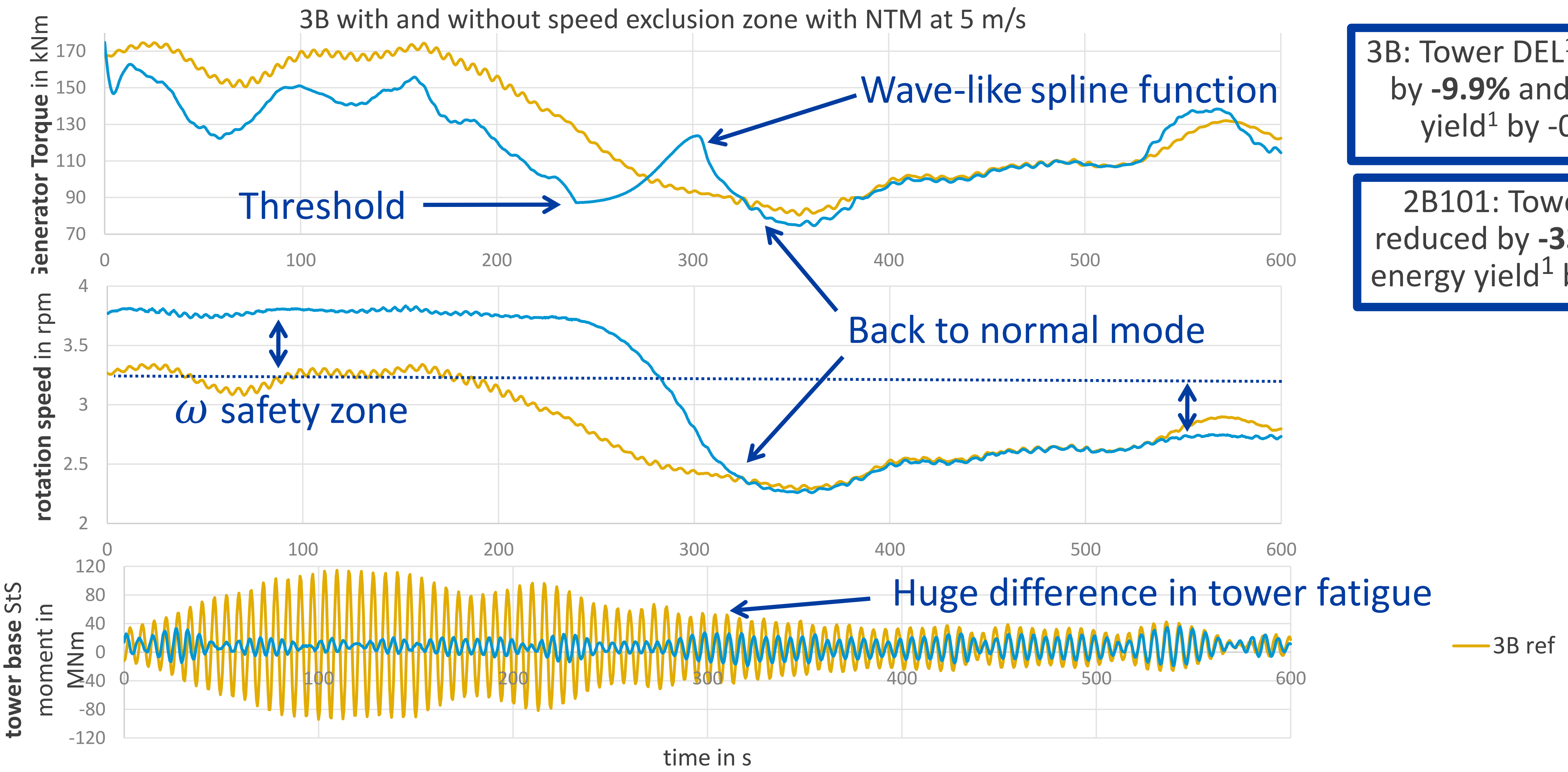
Load Summary

	absolute			relative (2B/3B)	
DLC 1.2 – Fatigue	3B ref	2B101 Twin	2B101 Teeter	2B101 Twin	2B101 Teeter
blade root edgewise bending moment Mx DEL in Nm	71002740	105901159	92506189	1.49	**1.30**
blade root flapwise bending moment My DEL in Nm	45376077	73257074	49189214	1.61	**1.08**
blade root torsional moment Mz DEL in Nm	737543	1295715	1104815	1.76	1.50
yaw roll moment Mx DEL in Nm	2473398.18	3215212	1869201	1.30	**0.76**
yaw nodding moment My DEL in Nm	21975649	35467791	7237193	1.61	**0.33**
yaw torsional moment Mz DEL in Nm	21109974.8	33656891	5252466	1.59	**0.25**
hub stationary nodding moment My DEL in Nm	21253726	34271970	3745416	1.61	**0.18**
hub stationary yawing moment Mz DEL in Nm	20472812.5	33068200	3798590	1.62	**0.19**
hub rotating moment My DEL in Nm	26353208.5	48706135	3574	1.85	**0.00**
hub rotating moment Mz DEL in Nm	26290111.1	8040764	6399148	0.31	**0.24**
main shaft rotating bending DEL at first bearing in worst direction in Nm	38786740	47984555	34044479	1.24	**0.88**
tower base bending moment DEL in worst direction in Nm	42072893	58465556	42917463	1.39	1.02
Pitch mean ADC (actuator duty cycle) in deg/600s	115	568	597	4.93	5.17
pitch rotations in 25 years	335149	1650827	1734346	4.93	5.17
mean power in W (if online)	12252621	12196080	12187187	1.00	0.99
Extreme loads					
Blade root flapwise moment My in Nm	143218962	216860713	183836849	1.51	1.28
Blade root edgewise moment Mx in Nm	70687995	90006419	101775588	1.27	1.44
Yaw nodding My in Nm	-114572990	133372140	-99928797	1.16	0.87
Yaw roll Mx in Nm	41742905	45627127	38716177	1.09	0.93
Yaw torsional Mz in Nm	113998910	194570873	23921628	1.71	0.21
Yaw "gravity" force Fz in N	-17228985	-16114630	-16084946	0.94	0.93
minimum tip to tower clearance in m	5.62	6.77	5.93	1.20	1.06
generator mass [kg] scaled by faster rotation speed	523,960	483,830	483,830	0.92	0.92
blade mass [kg]	117,894	164,402	138,314	1.39	1.17
material cost share jacket	0.59398				

could be a game changer for floating turbines

- Be aware for blade masses and loads that the blades of the two-bladed turbines are ~2% larger.
- All DELs have a reference frequency of 1Hz and all values are Rayleight distribution weighted with 11.4m/s rated wind speed
- If further values are desired, feel free to contact fabian.anstock@haw-hamburg.de

Speed exclusion zone – how does it work? Example



3B: Tower DEL[1] reduced by **-9.9%** and energy yield[1] by -0.03%

2B101: Tower DEL[1] reduced by **-33.8%** and energy yield[1] by -0.17%

[1] DLC 1.2 with 0°, +-8° yaw and Rayleigh distribution with 11.4 m/s mean wind speed

20 MW VolturnUS towereigenfrequency examples

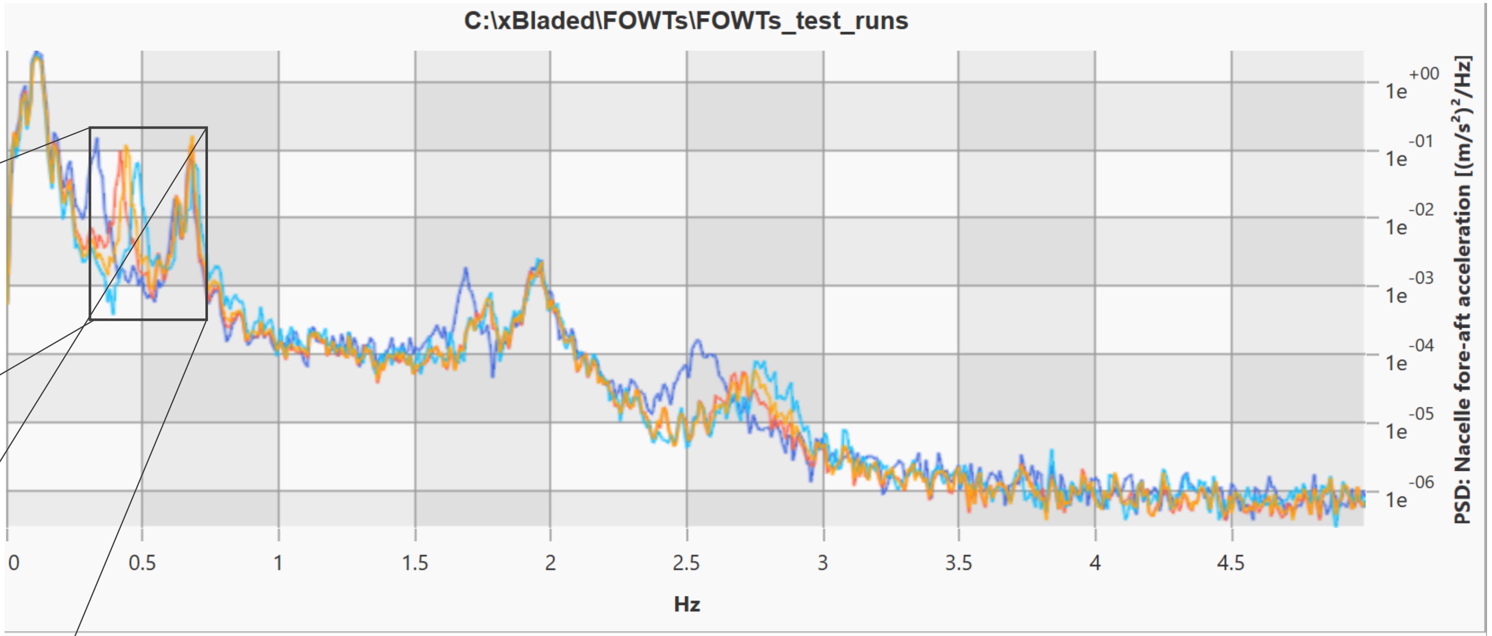
Tower frequency variation:

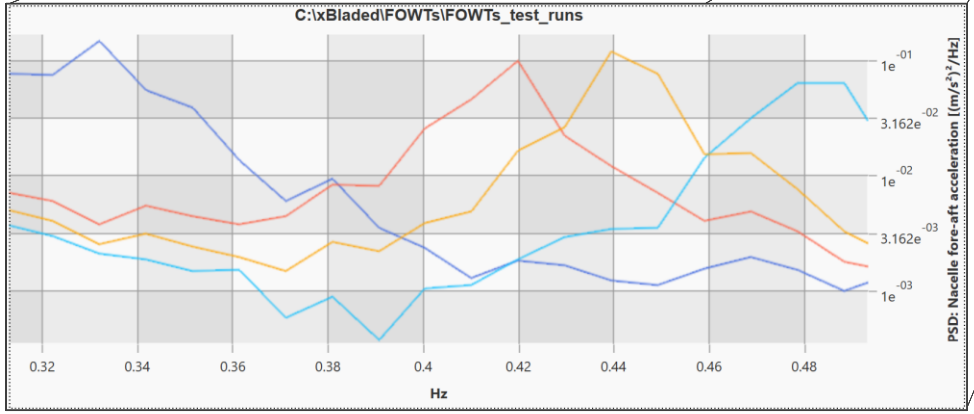
INNWIND original: 0.33 Hz, 1408823 t

Max Diameter : 0.42 Hz, 1894039 t (+38%)

+ HIPERWIND D/t : 0.48 Hz, 2625289 t, (+95%)

+ interpolated D/t: 0.44 Hz, 2123969 t, (+56%)





Group by ◉ Variable ○ Calculation — Collapse | Expand | Edit | Export | ☐ Show Legend

	Unit	Colour	Minimum	Mean	Maximum
4)					
uns\3B20Volturn_DLC61_v02_tower1_reference	m/s²	(blue)	-1.59e+00	2.953e-03	1.371e+00
uns\3B20Volturn_DLC61_v03_tower2_max_diameter	m/s²	(red)	-1.734e+00	2.311e-03	1.901e+00
uns\3B20Volturn_DLC61_v03_tower3_max_diameter_HIPERWIND_thickness_ratio	m/s²	(light blue)	-1.906e+00	3.304e-04	1.588e+00
uns\3B20Volturn_DLC61_v03_tower4_max_diameter_n_interpolated_thickness	m/s²	(orange)	-1.796e+00	2.123e-03	1.876e+00