Development of a 12MW Floating Offshore Wind Turbine

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Outline

- Introduction
- UOU 12MW FOWT model
- Modified Control System
- Numerical Simulation
- Design Load Cases
- Novel Offshore Floater
- Conclusion

1. Introduction

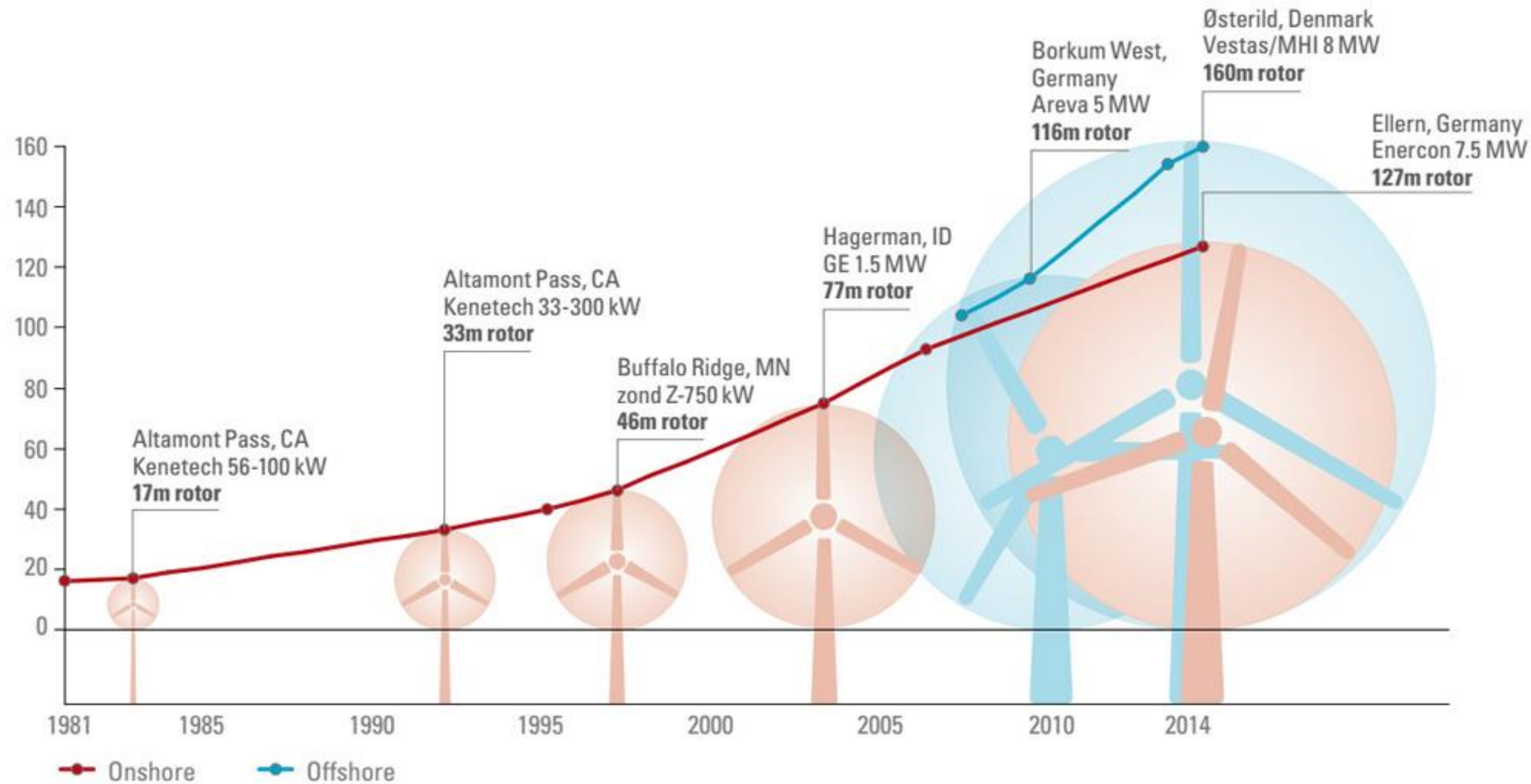
Ulsan , Korea

Wikipedia 2014

Light through Darkness

Growth in Size of Wind Turbine

- Turbines have grown larger and taller to maximize energy capture



Source : http://www.sbcenergyinstitute.com/Publications/Wind

Critical Needs for FOWTs

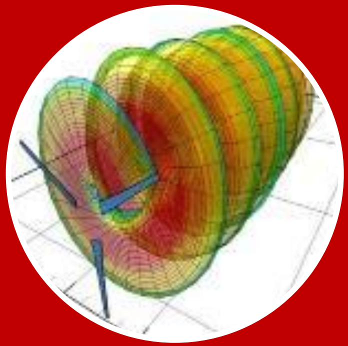
- Responsible and Sustainable Ocean Economy 2030 -

Industry	Compound annual growth rate for GVA between 2010 and 2030	Total change in GVA between 2010 and 2030	Total change in employment between 2010 and 2030
Industrial marine aquaculture	5.69%	303%	152%
Industrial capture fisheries	4.10%	223%	94%
Industrial fish processing	6.26%	337%	206%
Maritime and coastal tourism	3.51%	199%	122%
Offshore oil and gas	1.17%	126%	126%
Offshore wind	24.52%	8 037%	1 257%
Port activities	4.58%	245%	245%
Shipbuilding and repair	2.93%	178%	124%
Maritime equipment	2.93%	178%	124%
Shipping	1.80%	143%	130%
Average of total ocean-based industries	**3.45%**	**197%**	**130%**
Global economy between 2010 and 2030	**3.64%**	**204%**	**120%[1]**

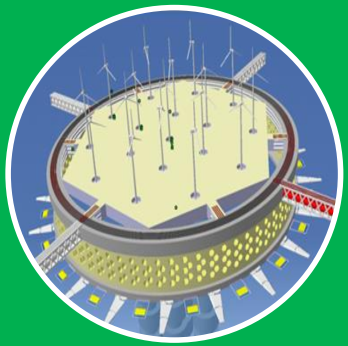
1. Based on projections of the global workforce, extrapolated with the UN medium fertility rate.

Source: Authors' calculations based on OECD STAN, UNIDO INDSTAT, UNSD; Lloyd's Register Group (2014; 2013); World Bank (2013); IEA (2014); FAO (2015).

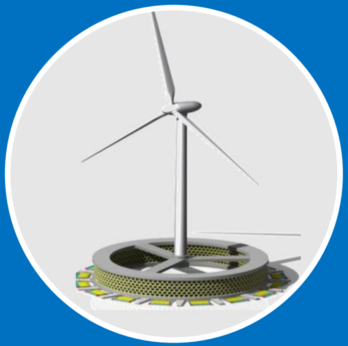
Why do we need FOWT ?



Stronger & Better wind



Solution for noise & insufficient space

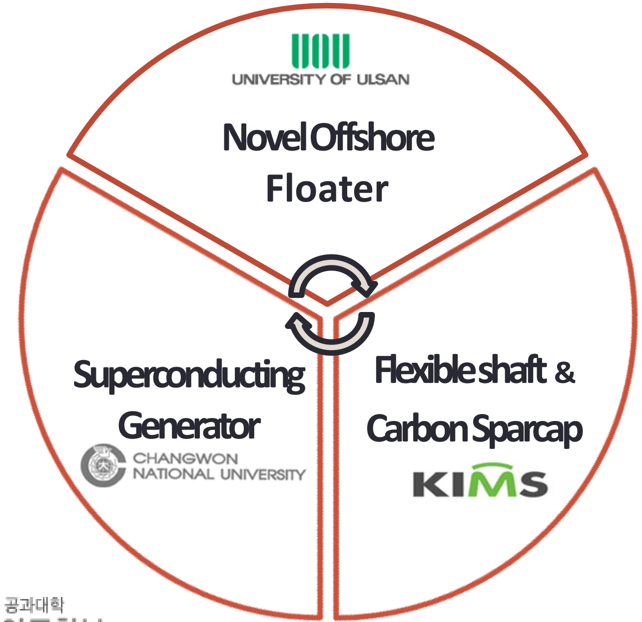


Solution for energy shortage in future

Why Floating Offshore Wind Turbine?

Objective (Motive)

- Why ?
  - ✓ Enlargement in size & capacity considering LCOE
  - ✓ Needs for innovative Floating Offshore Wind Turbines
  - ✓ Light through darkness
- How ?
  - ✓ Novel offshore floater without mooring lines
  - ✓ To reduce the Tophead mass
  - ✓ SCSG, Flexible Composite Shaft, Carbon Sparcap

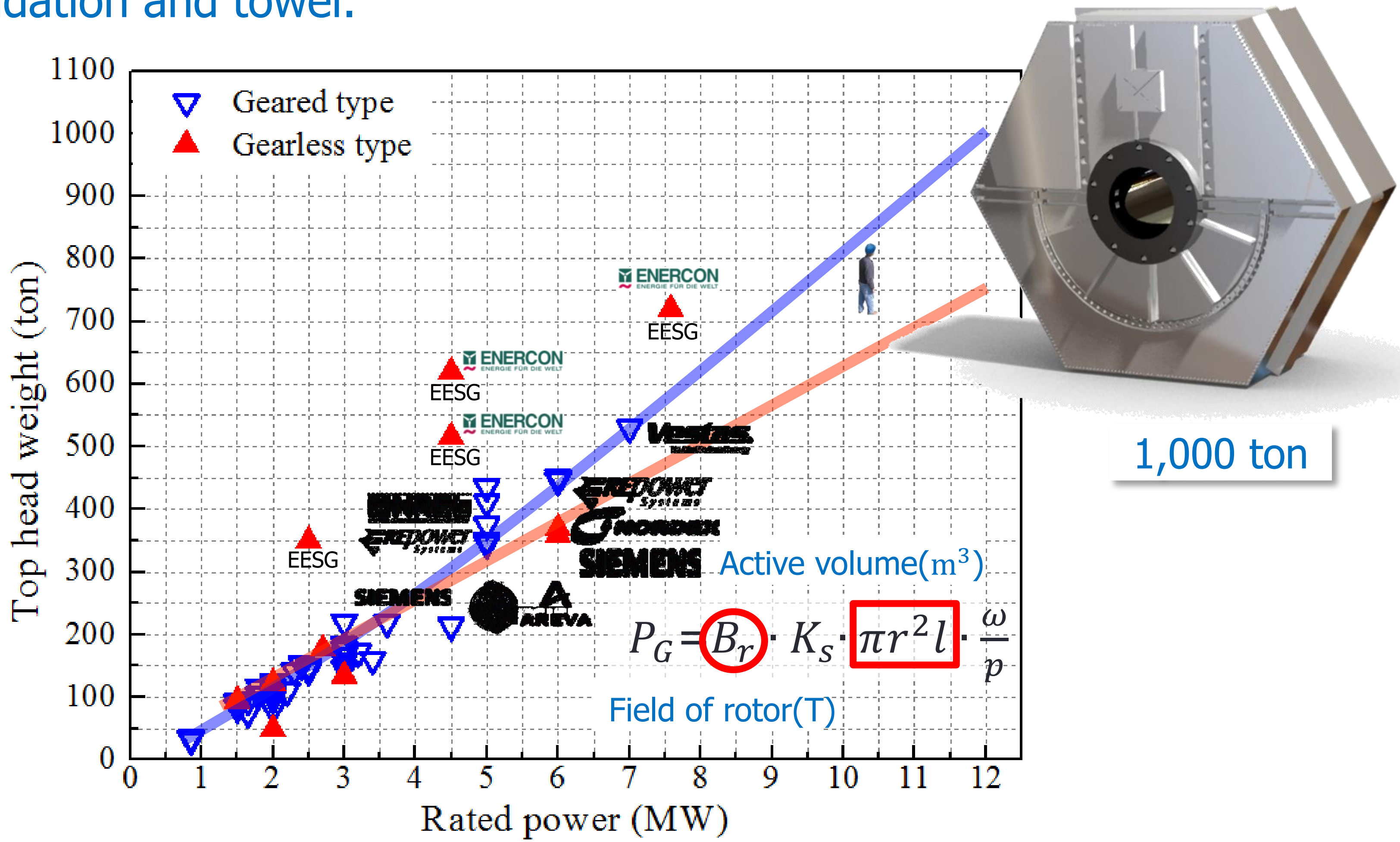


12MW FOWT

Target

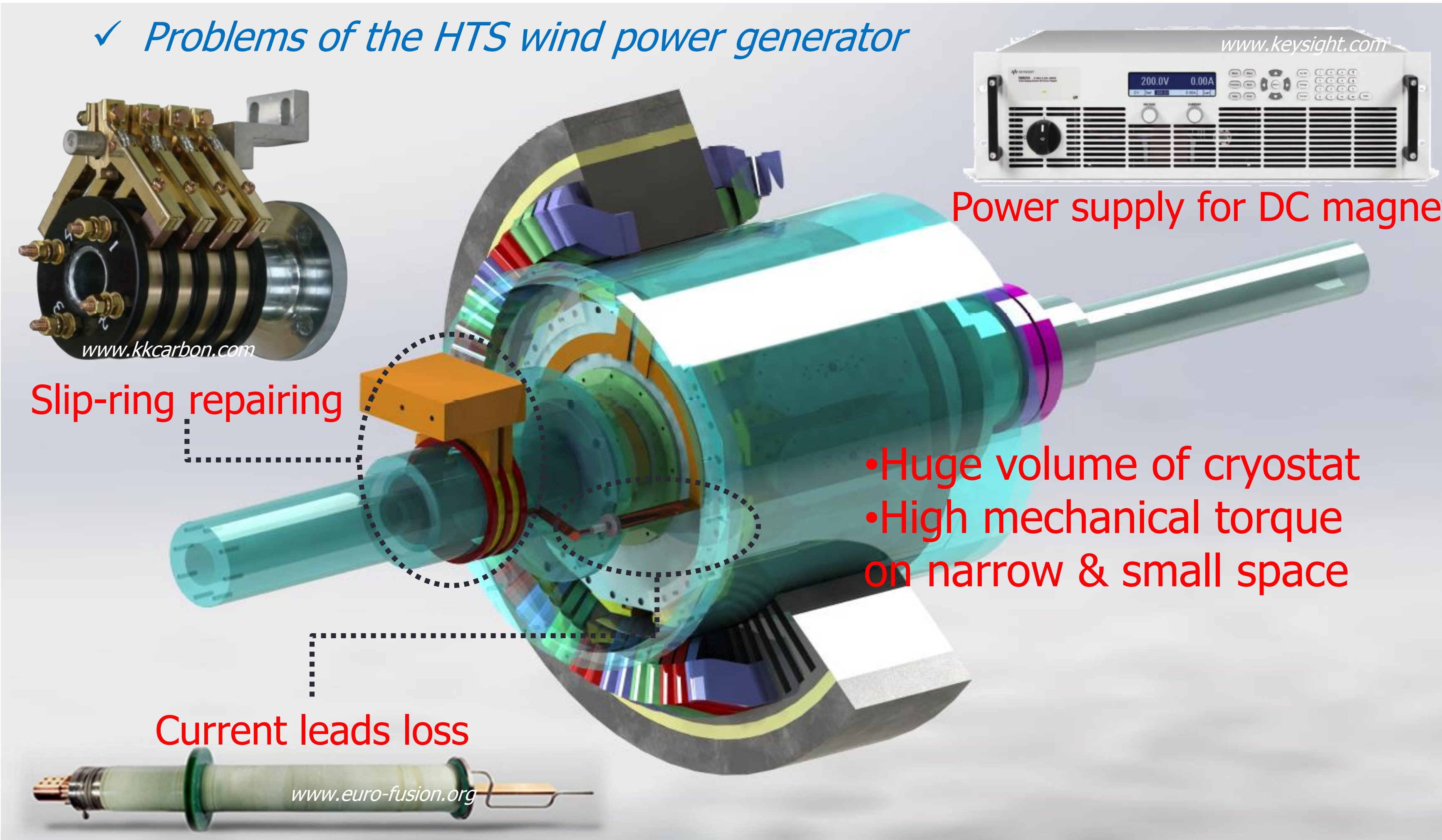
Reason why we use a superconducting generator

The heavy top head causes the high mechanical stress and high cost of foundation and tower.



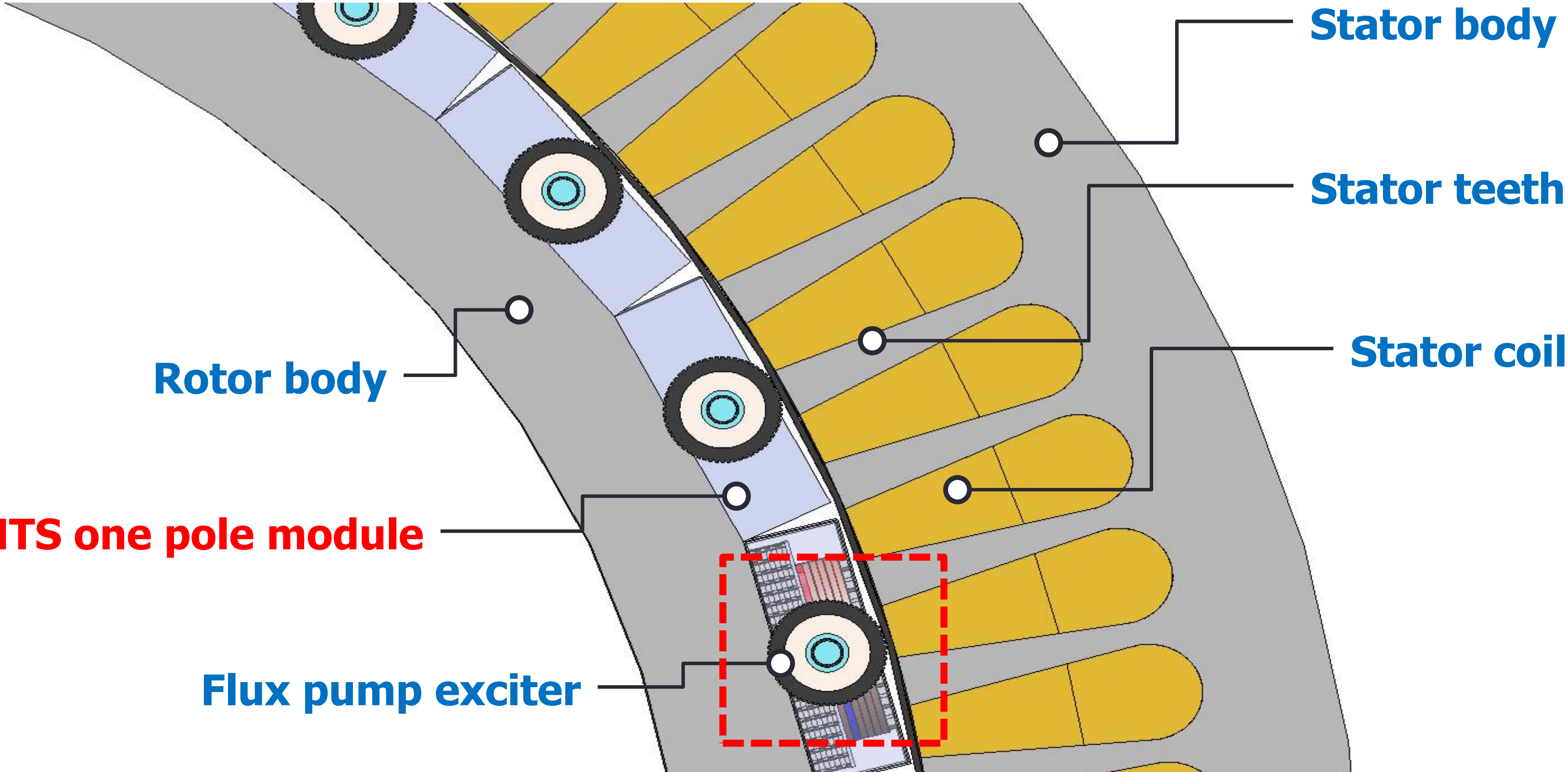
Source : Changwon National University, CAPTA

Suggestion of a new technology for the 12 MW



Source : Changwon National University, CAPTA

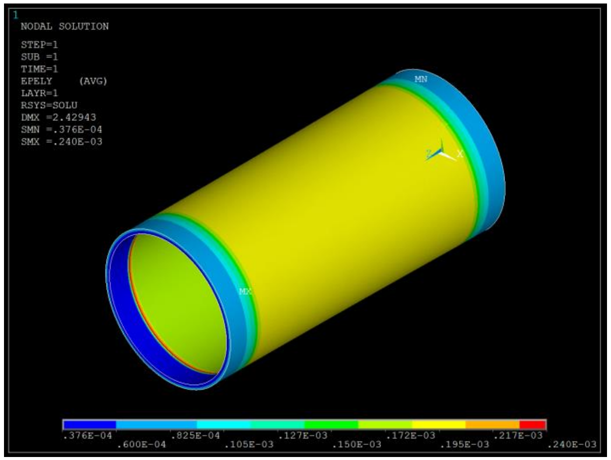
Modularized generator for the 12MW



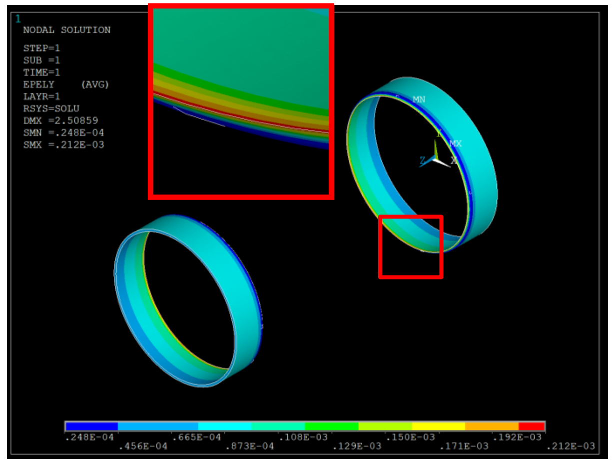
The modularization of the generator enables a smaller cryogenic volume, an easier repair, assembly, and maintenance of the HTS field coil. Modularization will be suitable for commercial mass production and will increase the operational availability of HTS generators in the wind turbine.

Source : Changwon National University, CAPTA

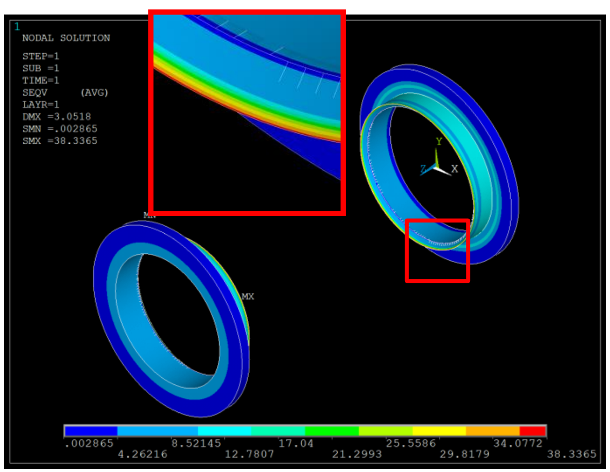
Detailed design for composite flexible shaft



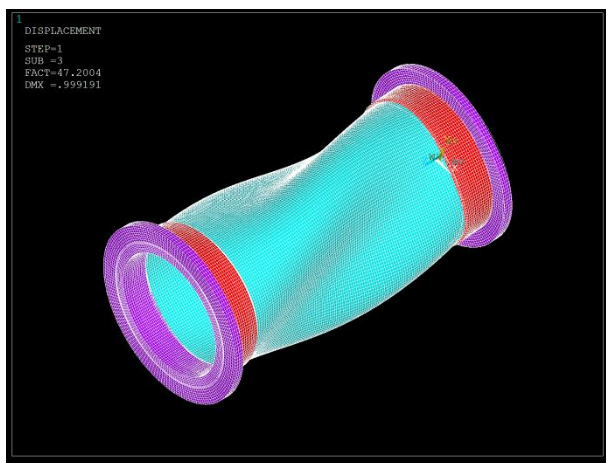
Glass composite shaft



Carbon composite pad-up



Metal flanged part



Global buckling

- Analysis for ultimate & fatigue strength
- Total Mass : 51.86 ton

	M.S.
Glass composite shaft	0.22 (First-ply failure)
Carbon composite pad-up	0.56 (First-ply failure)
Metal flanged part	0.88 (Von-mises stress)
Global buckling	46.2

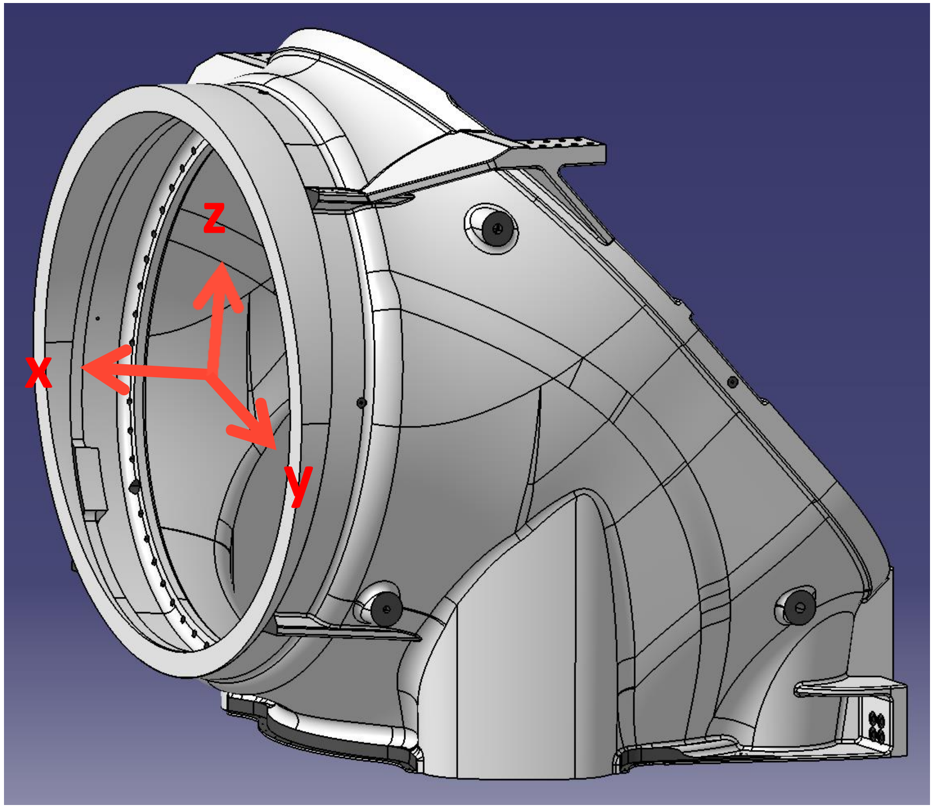
Source : Korea Institute of Materials Science(KIMS)

Detailed design for new support structure

➢ Bending load case

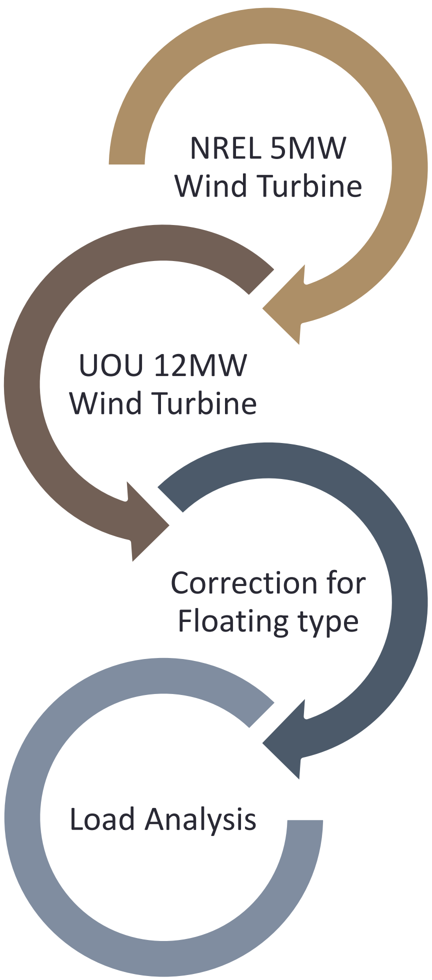
Case	My (MNm)	Mz (MNm)
1	-37.69	4.68
2	66.55	5.13
3	-2.40	-44.09
4	-6.10	47.32

Source : Korea Institute of Materials Science(KIMS)



UOU 12MW Wind Turbine Model

Design Process

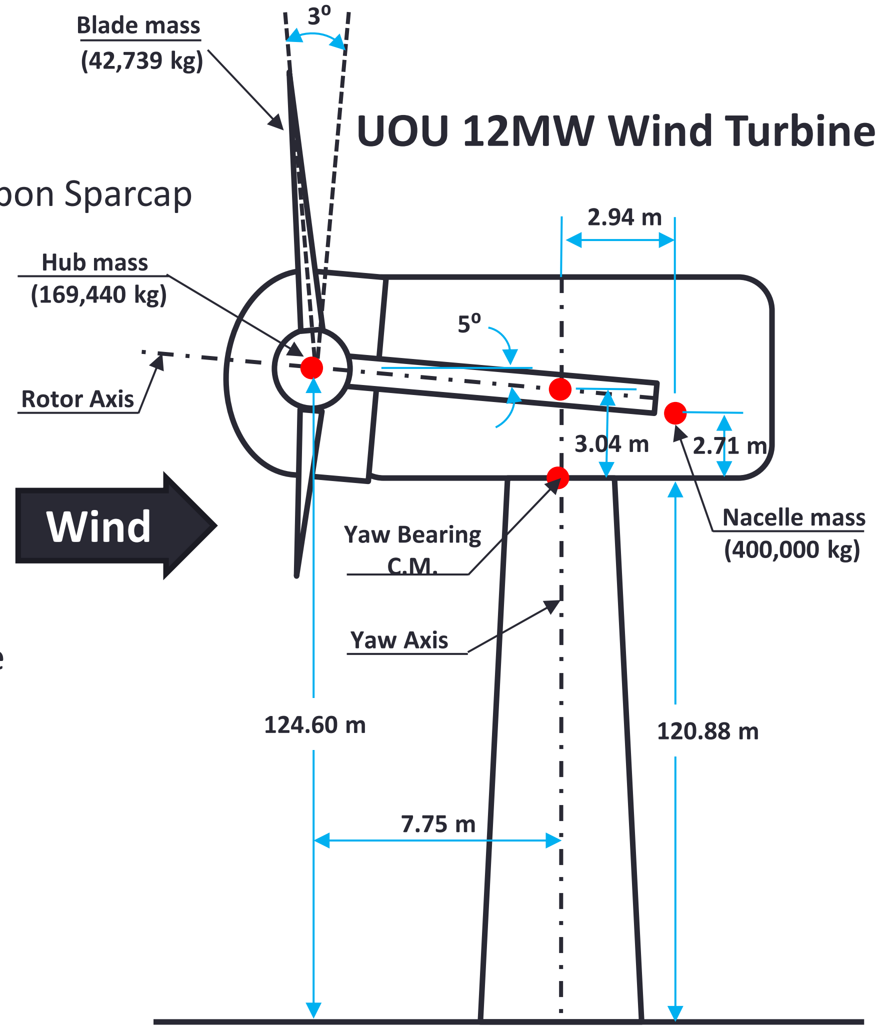


- Upscaling process
  SCSG/Flexible Shaft/Carbon Sparcap

- Blade (CFRP)
- Tower
- Control
- Platform

- Negative damping issue
- Tower 3P issue

- IEC61400-1
- IEC61400-3
- IEC61400-3-2



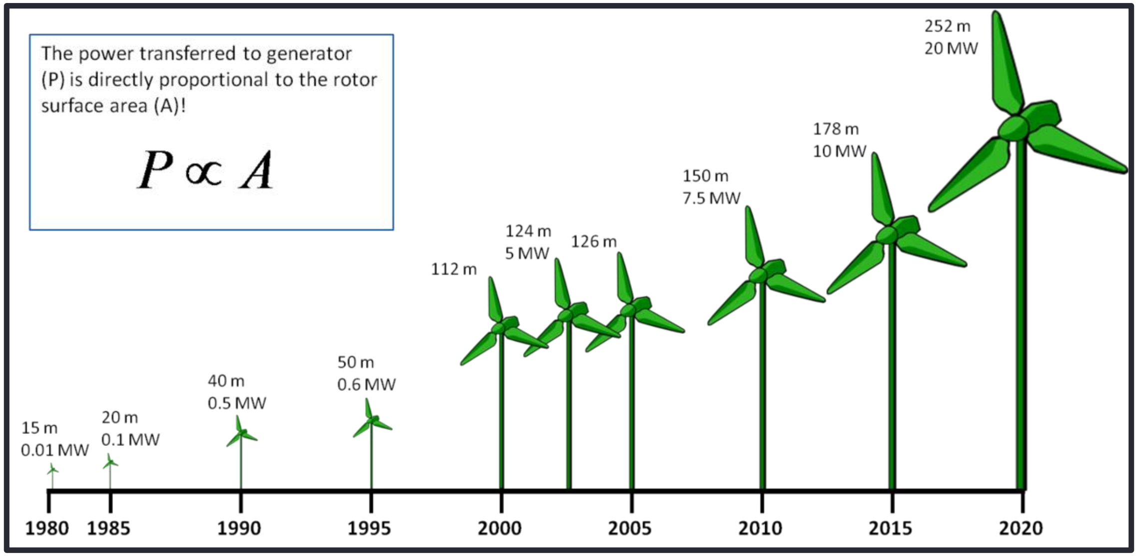
Design Summary

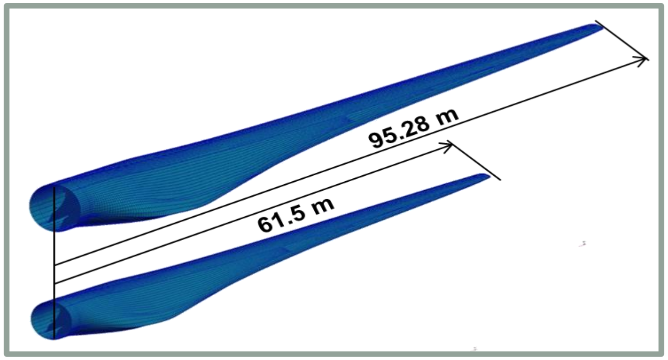
Rating	5 MW	12 MW
Rotor Orientation	Upwind, 3 Blades	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox	Low Speed, Direct Drive (SCSG)
Rotor, Hub Diameter	126 m, 3 m	195.2 m, 4.64 m
Hub Height	90 m	124.6 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s	3 m/s, 11.2 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm	3.03 rpm, 8.25 rpm
Overhang, Shaft Tilt, Pre-cone	5 m, 5°, 2.5°	7.78 m, 5°, 3°
Rotor Mass	110,000 kg	297,660 kg
Nacelle Mass	240,000 kg	400,000 kg (*Target*)
Tower Mass (for offshore)	249,718 kg	782,096 kg

2. UOU 12MW FOWT Model

Scaling Laws for 12MW power production

- $P = C_p * \frac{1}{2}\rho A V^3$
- $Scale\ ratio = \lambda = \sqrt{\frac{12MW}{5MW}} = 1.549$
- Blade length : NREL 5MW(61.5m) -> UOU 12MW(95.28 m)



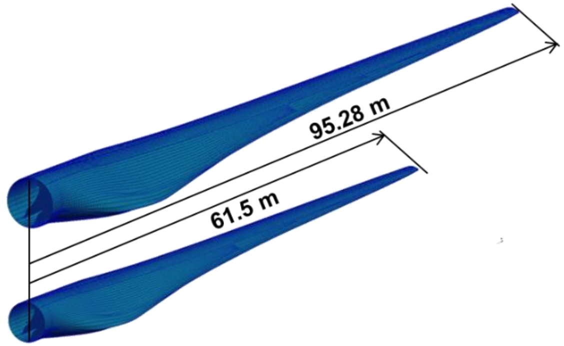


➢ Same geometry(Airfoil) with NREL 5MW blade

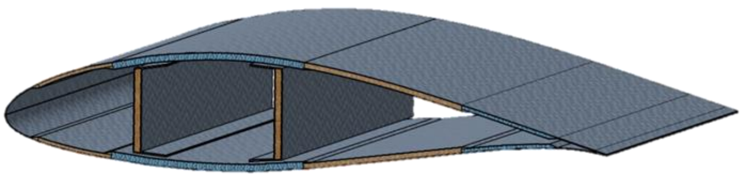
Source : EWEA, Wind energy—the facts: a guide to the technology, economics and future of wind power, 2009.

12MW Carbon blades

- 61.5 (m) 5MW glass blade : 17.7 ton
  → 95.28 (m) 12MW glass blade : 62.6 ton (Too heavy)
  → 95.28 (m) 12MW carbon (sparcap) blade : 42.7 ton



Sparcap
(43% of the total weight – 5MW class IIA)



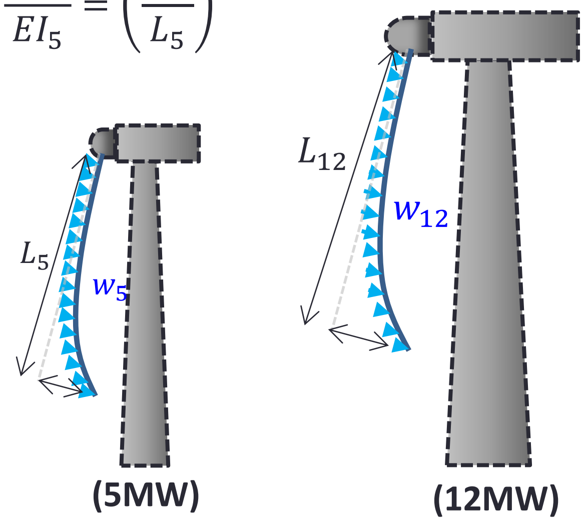
	0° Stiffness [Gpa]	Density [kg/m³]	Blade Weight [ton]	Center of Gravity [m]
CFRP	130	1572	42.7 (Carbon Sparcap)	31.8
GFRP	41.5	1920	62.6	31.8

Source : Korea Institute of Materials Science(KIMS)

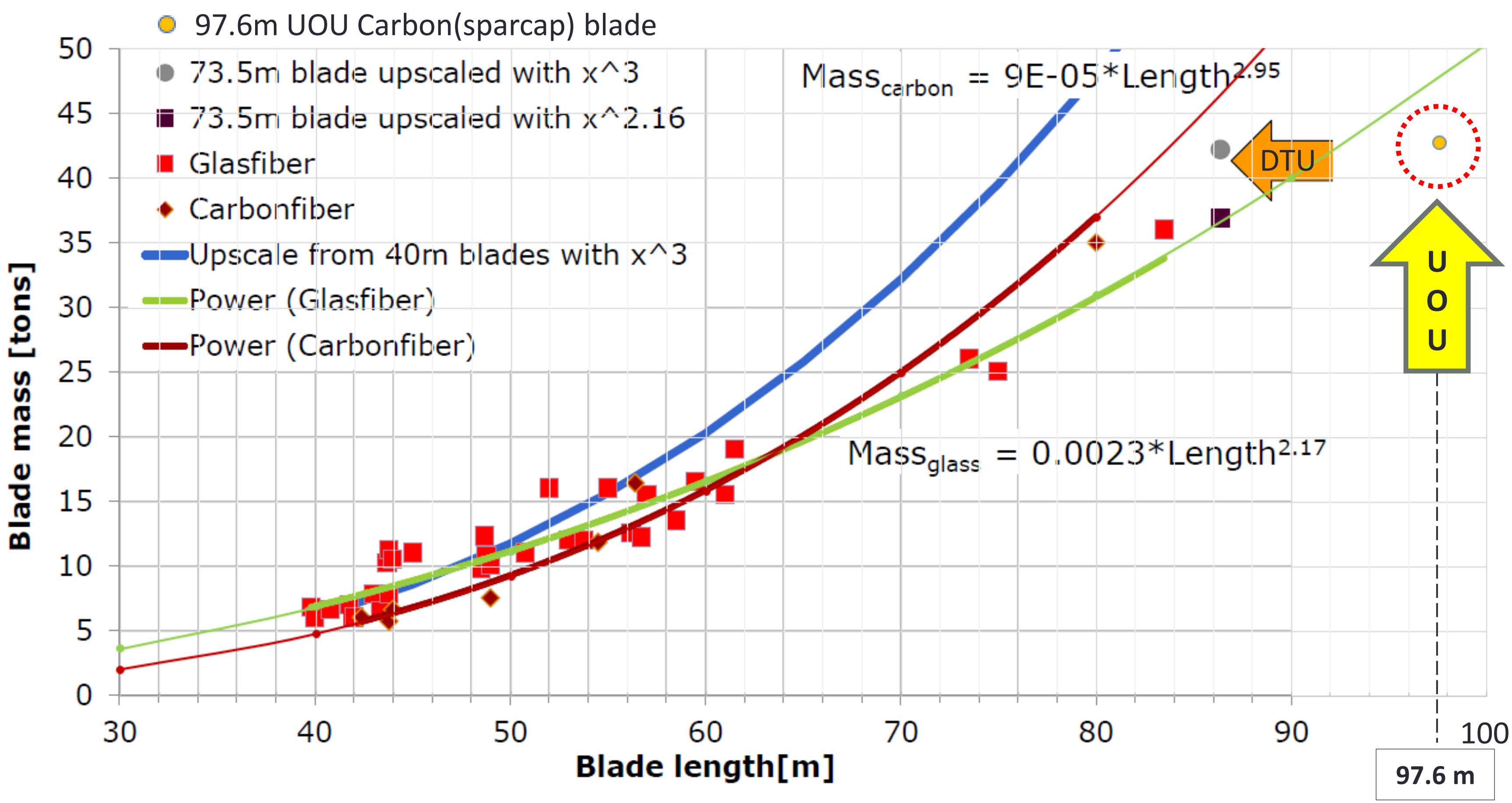
N.F. [Hz]	1st Flapwise	2nd Flapwise	1st Edgewise	2nd Edgewise
12MW Blade	0.5770	1.6254	0.8920	3.2676

- Scale-up blade properties(deflection)

$$\frac{EI_{12}}{EI_5} = \left(\frac{L_{12}}{L_5}\right)^4$$



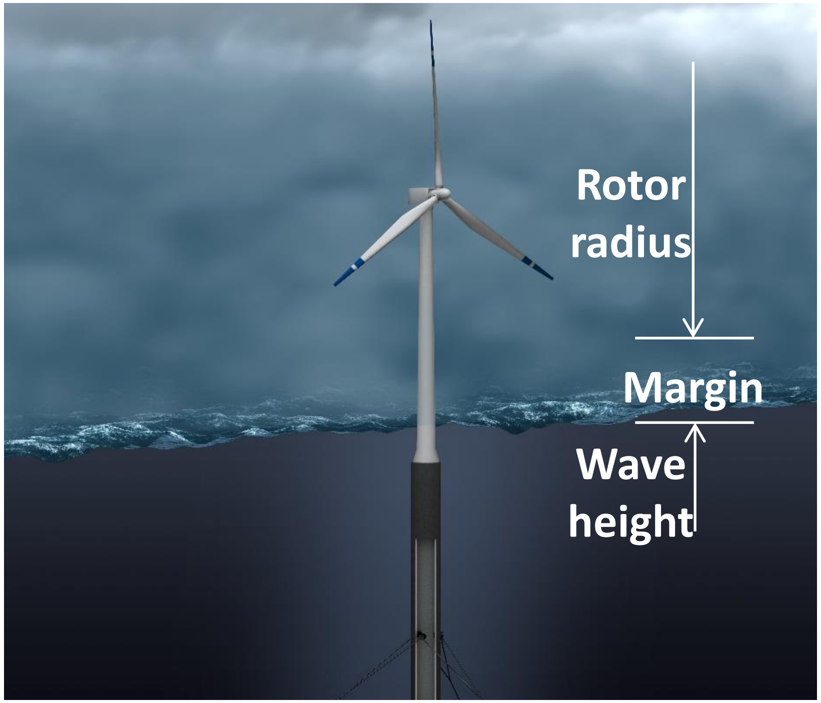
How the blade compares to existing ones



Source : C. Bak, "The DTU 10-MW Reference Wind Turbine", 2015(DTU)

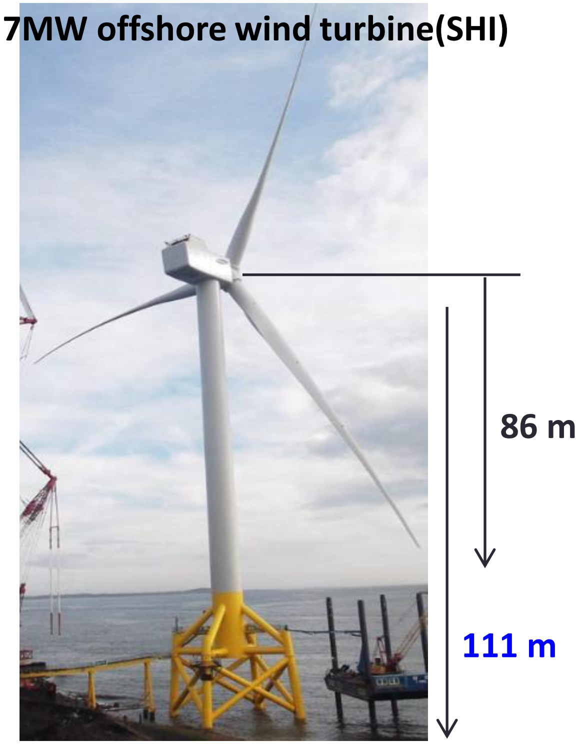
Hub height

- Nacelle target mass: 400 ton, Hub mass: 169.4 ton (scale-up)
- Hub height :
  Rotor radius + Extreme wave height (half) with 50-year occurrence × S.F. of 1.8
  → 97.6 + 30.0 / 2 × 1.8 = 124.6 m



Source : Statoil –hywind (Statoil.com)

7MW offshore wind turbine(SHI)



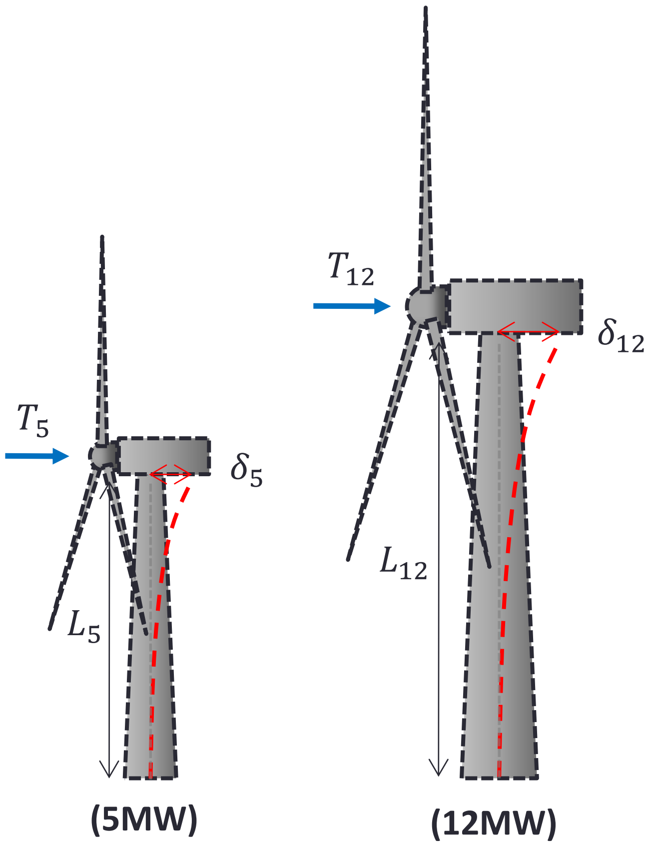
(cf. 86.0 + 30.0 / 2 × 1.8 = 113 m)

Source : http://www.ramboll.com/media/rgr/worlds-largest-turbine-installed

Scale-up tower properties

- **Scale up using <u>offshore tower</u> from OC4 definition(5MW : Height : 78.2 m , Weight : 249.718 ton)**
- **12MW "Material : steel, Height : 110.88 m, Weight : <u>782.096 ton</u> (scale-up)"**

  [cf. UPWIND report 2011 : 983 ton (10MW), 2,780 ton (20MW)]



- Beam deflection

$$\delta = \frac{TL^3}{3EI} \qquad \frac{\delta_{12}}{\delta_5} = \frac{L_{12}}{L_5} \qquad \frac{T_{12}}{T_5} = \frac{12\text{ MW}}{5\text{ MW}}$$

$$\frac{EI_{12}}{EI_5} = \frac{12L_{12}^2}{5L_5^2} \qquad T = C_t * \frac{1}{2}\rho A V^2$$

- Scale-up tower properties

$$\boxed{\frac{EI_{12}}{EI_5} = \frac{12L_{12}^2}{5L_5^2}}$$

(Beam deflection)

Scale-up platform properties

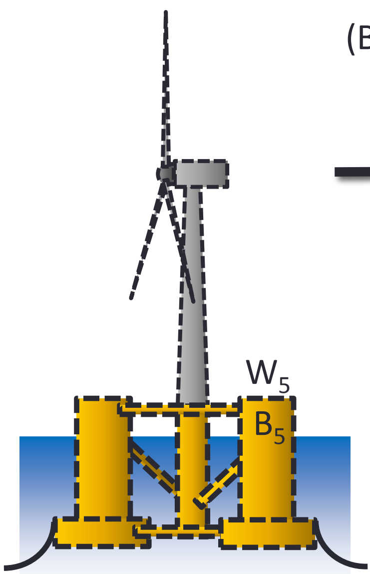
- Ratio of W_{12}(1480ton) to W_5(600ton)
- OC4 semi-submersible "displaced volume" 13,917m^3 (5MW) → 34,336m^3 (12MW)

- Scale up properties

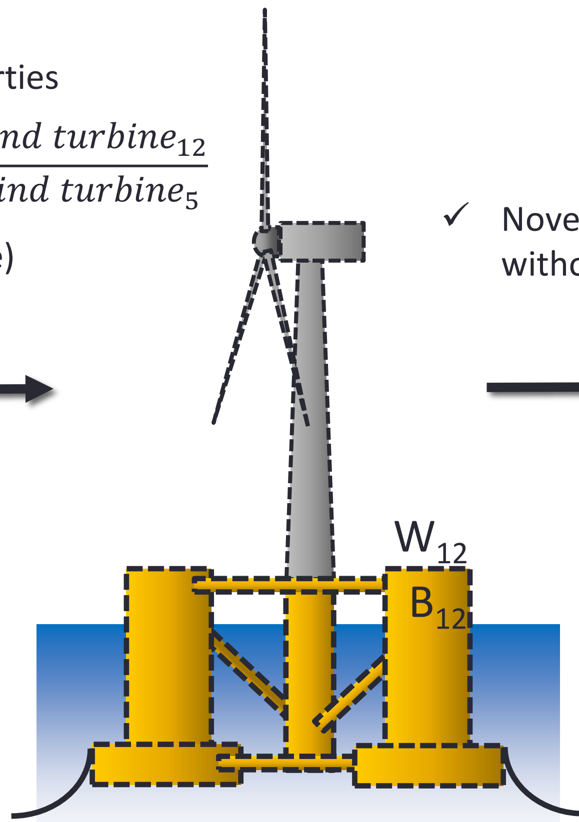
$$\frac{\rho g V_{12}}{\rho g V_5} = \frac{Weight\ of\ wind\ turbine_{12}}{Weight\ of\ wind\ turbine_5}$$

(Buoyancy force)

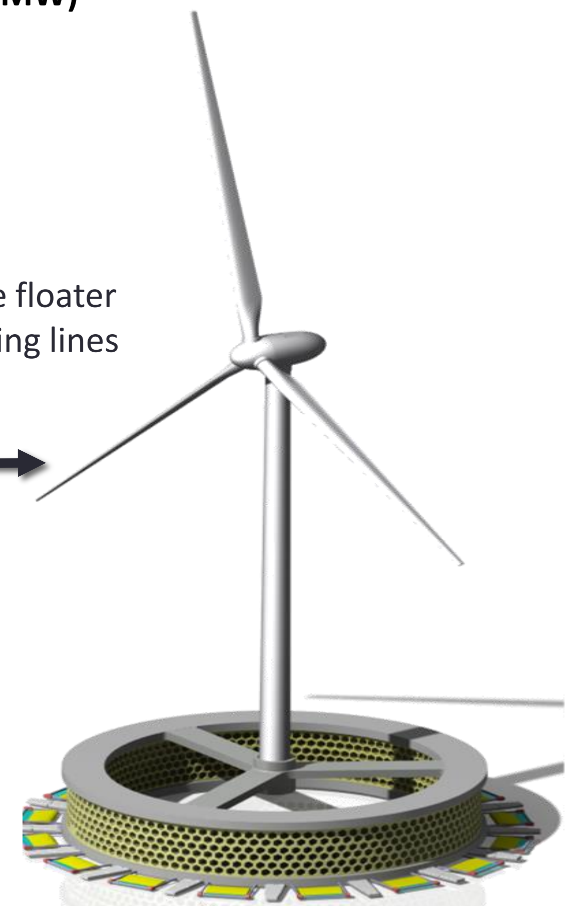
✓ Novel offshore floater without mooring lines



OC4 DeepCWind semi−submersible (5MW)



OC4 DeepCWind semi−submersible (12MW)



UOU 12MW FOWT

3. Modified Control System

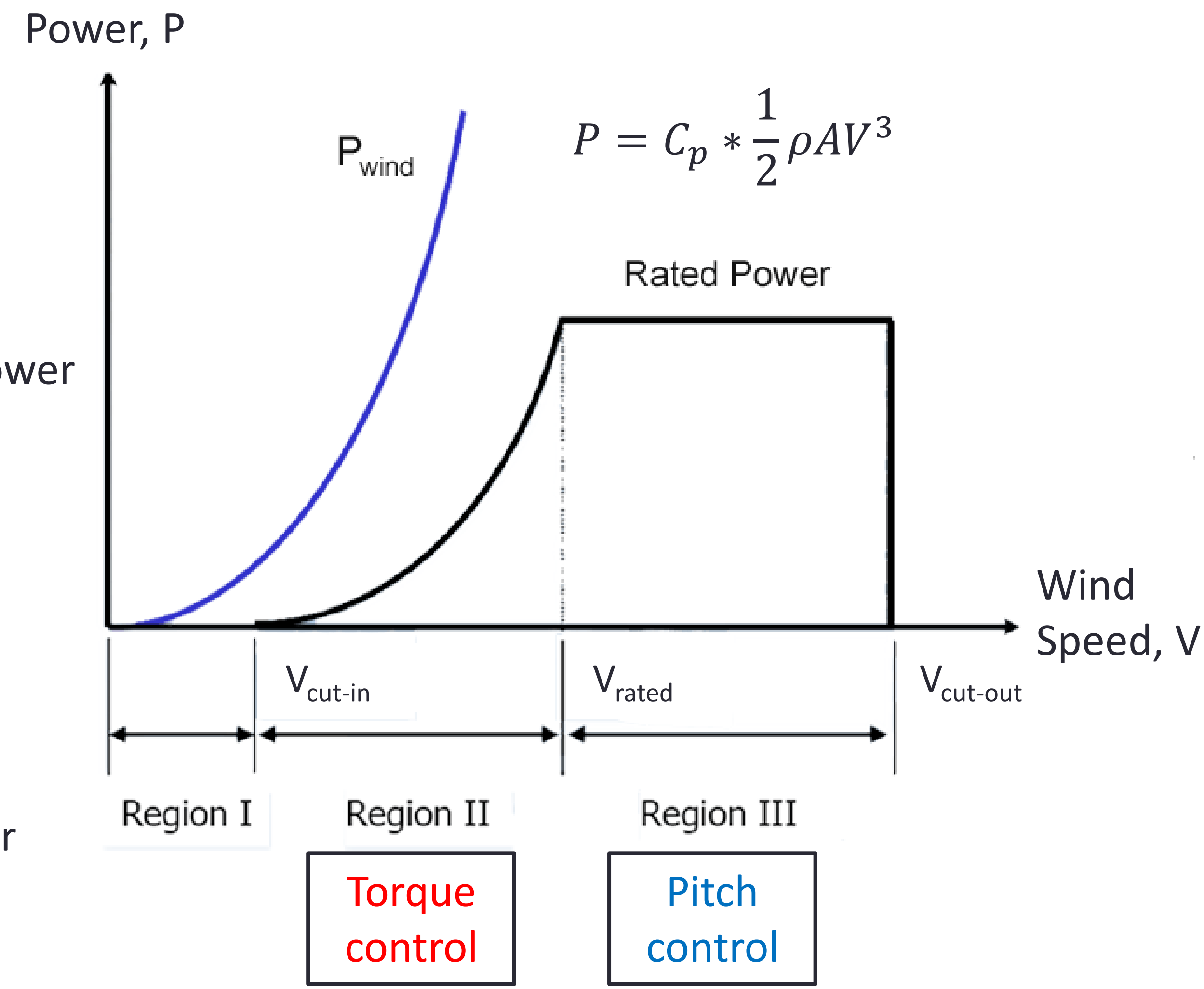
Wind Turbine Power Curve

Region II

- Torque Control
- Variable speed,
- Constant pitch,
- Target : Cp = Cp_max
- Maximize the optimum power

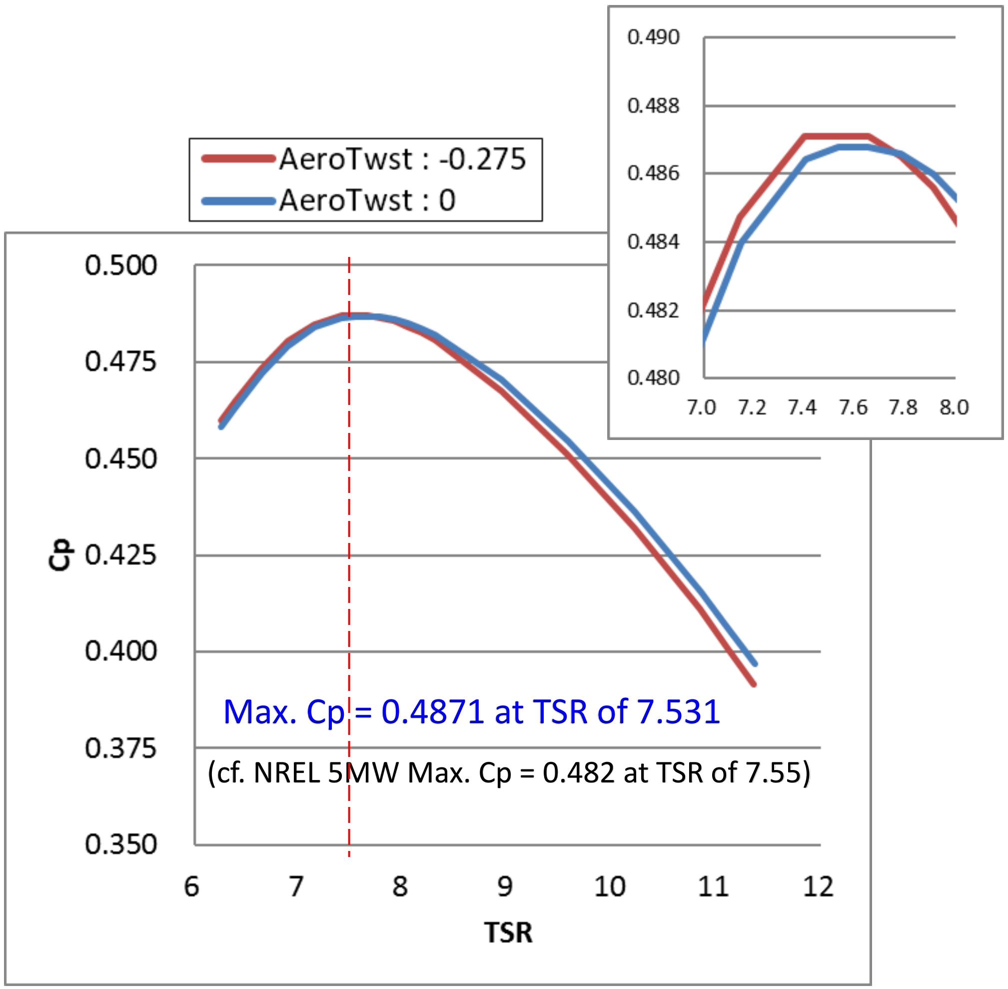
Region III

- Pitch Control
- Constant speed,
- Variable pitch,
- Target : P = P_rated
- Maintain the rated power



Source : https://www.e-education.psu.edu/aersp583/node/470

Maximum Cp and Optimal TSR(Tip Speed Ratio)



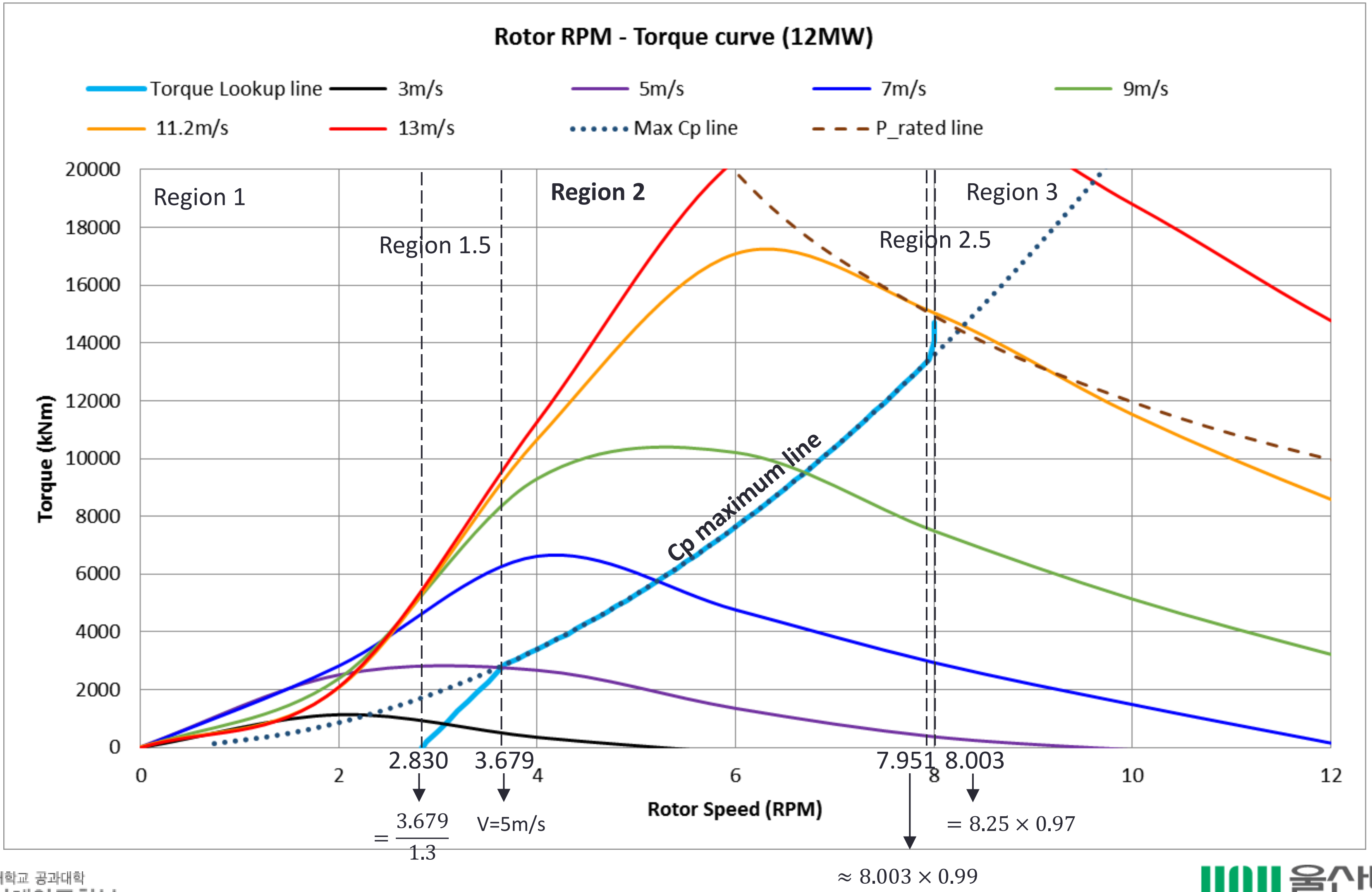
Cp – TSR curve

➤ Modification of the AeroTwst : - 0.275°

Node	Rnodes	AeroTwst	DRNodes	Chord	Airfoil Table
[-]	[m]	[°]	[m]	[m]	[-]
1	4.437	13.033	4.234	5.487	Cylinder1.dat
2	8.672	13.033	4.234	5.971	Cylinder1.dat
3	12.906	13.033	4.234	6.456	Cylinder2.dat
4	18.199	13.033	6.352	7.060	DU40_A17.dat
5	24.551	11.205	6.352	7.207	DU35_A17.dat
6	30.902	9.887	6.352	6.906	DU35_A17.dat
7	37.254	8.736	6.352	6.583	DU30_A17.dat
8	43.606	7.520	6.352	6.208	DU25_A17.dat
9	49.958	6.269	6.352	5.806	DU25_A17.dat
10	56.309	5.086	6.352	5.425	DU21_A17.dat
11	62.661	3.913	6.352	5.044	DU21_A17.dat
12	69.013	2.850	6.352	4.663	NC64_A17.dat
13	75.364	2.044	6.352	4.282	NC64_A17.dat
14	81.716	1.251	6.352	3.901	NC64_A17.dat
15	87.009	0.588	4.234	3.583	NC64_A17.dat
16	91.243	0.095	4.234	3.232	NC64_A17.dat
17	95.478	-0.169	4.234	2.198	NC64_A17.dat

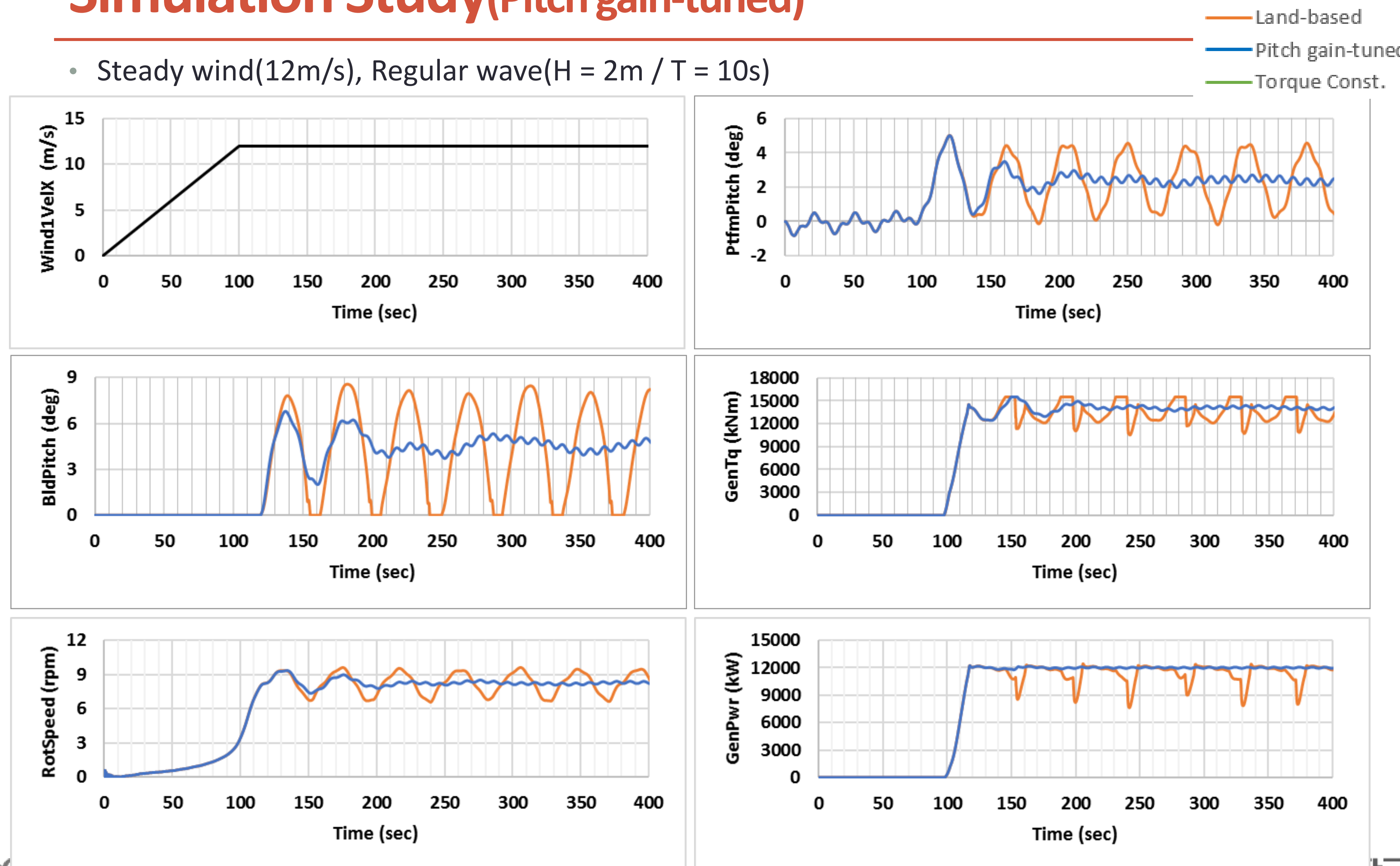
Aerodynamic properties

Torque Scheduling for 12MW



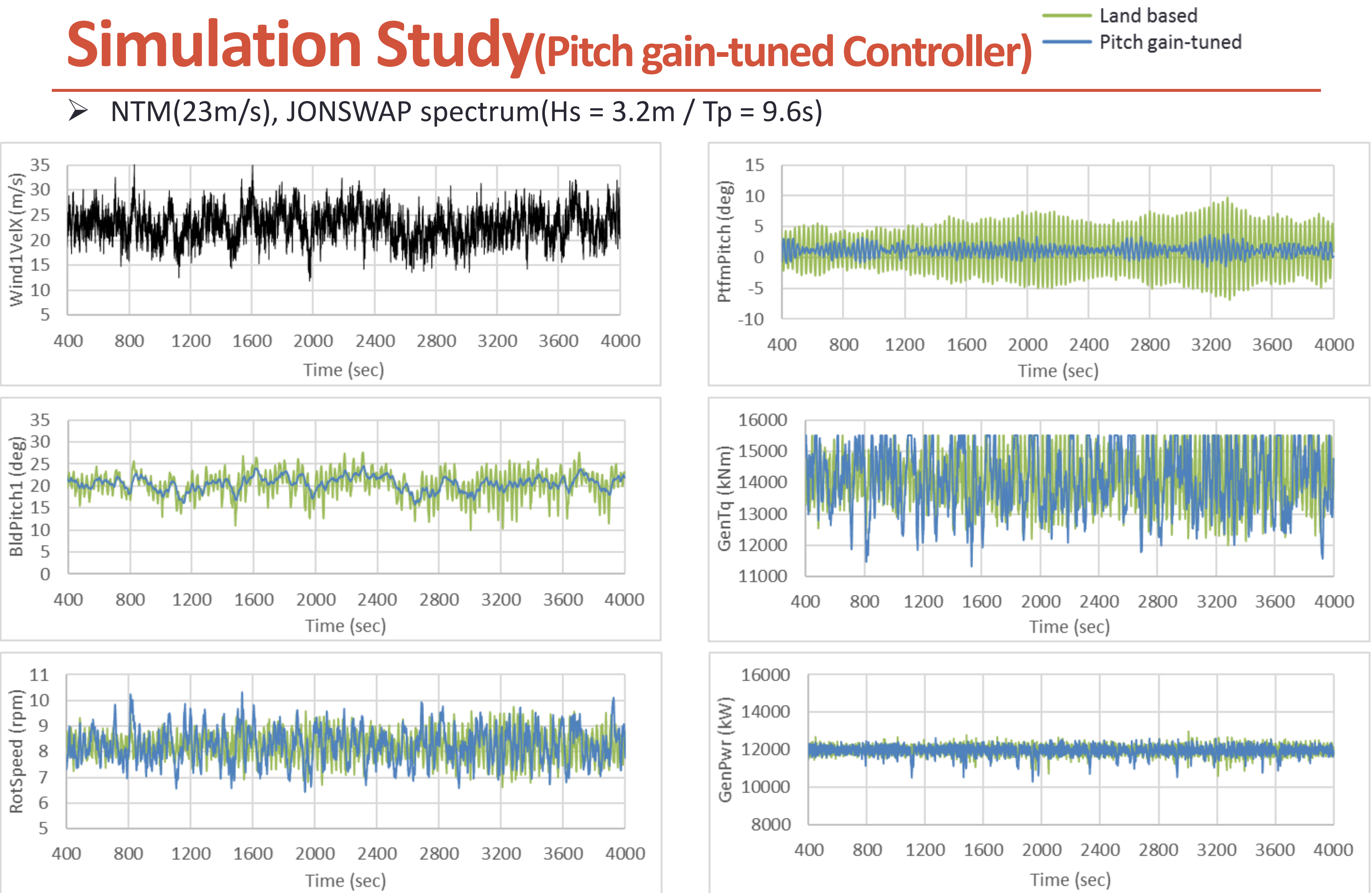
Simulation Study(Pitch gain-tuned)

- Steady wind(12m/s), Regular wave(H = 2m / T = 10s)

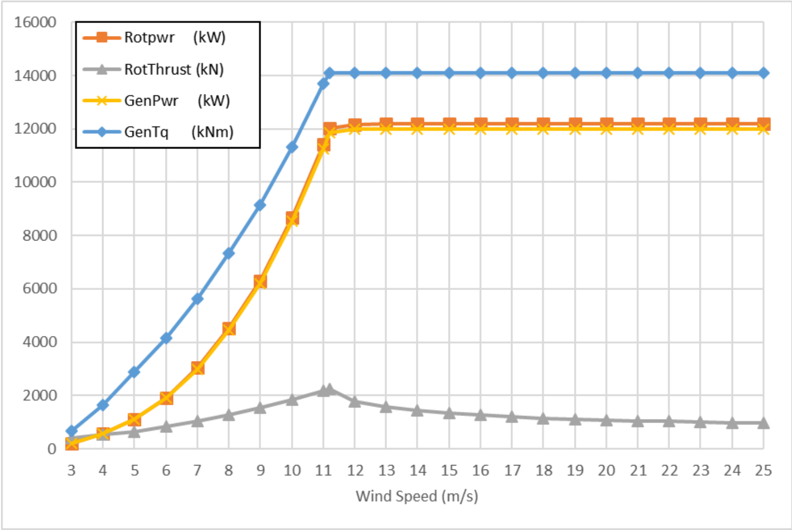


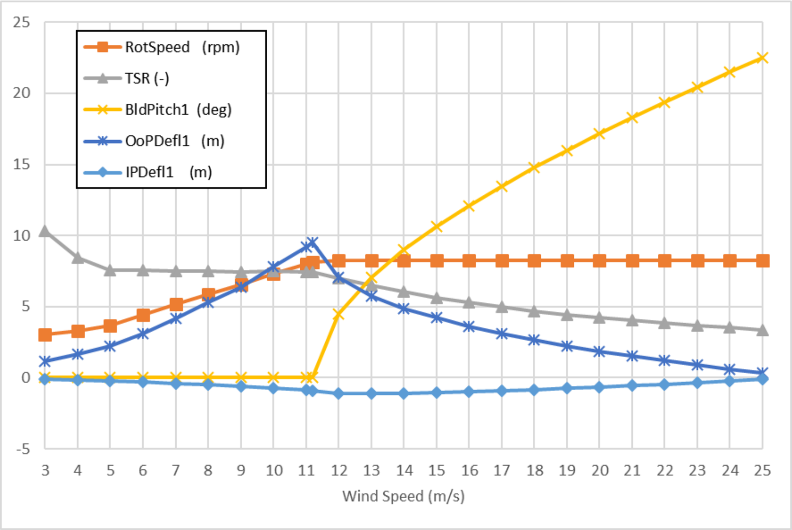
Simulation Study(Pitch gain-tuned Controller)

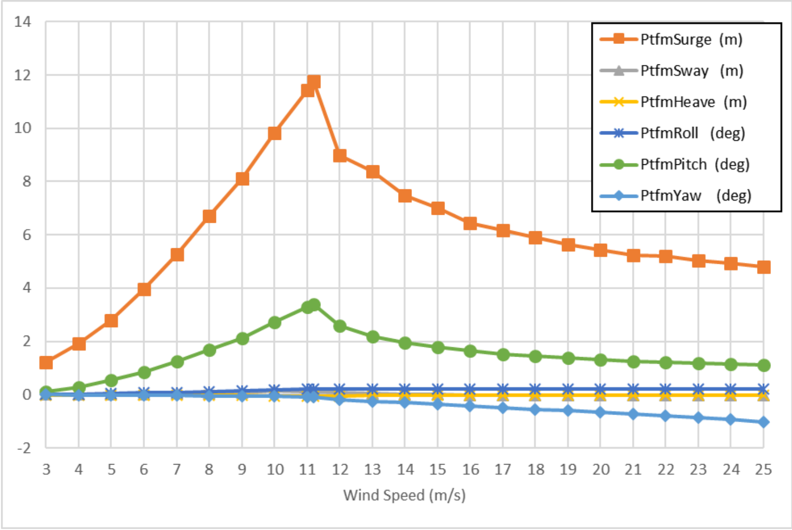
- NTM(23m/s), JONSWAP spectrum(Hs = 3.2m / Tp = 9.6s)

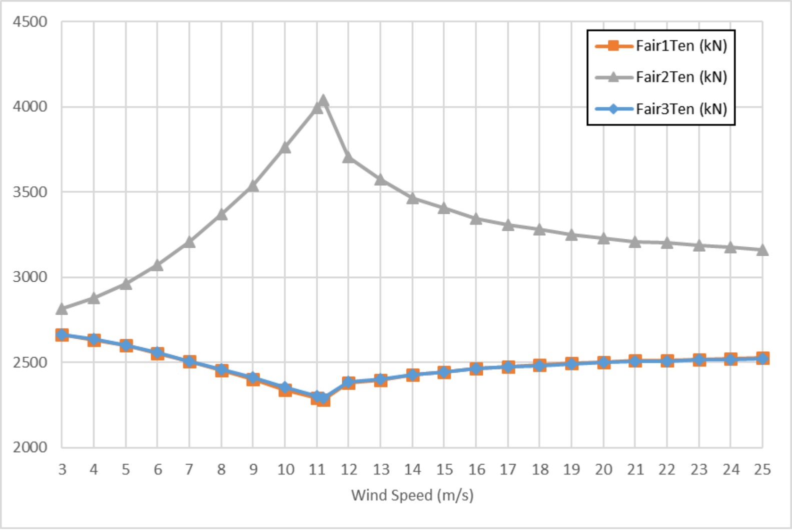


Steady state analysis



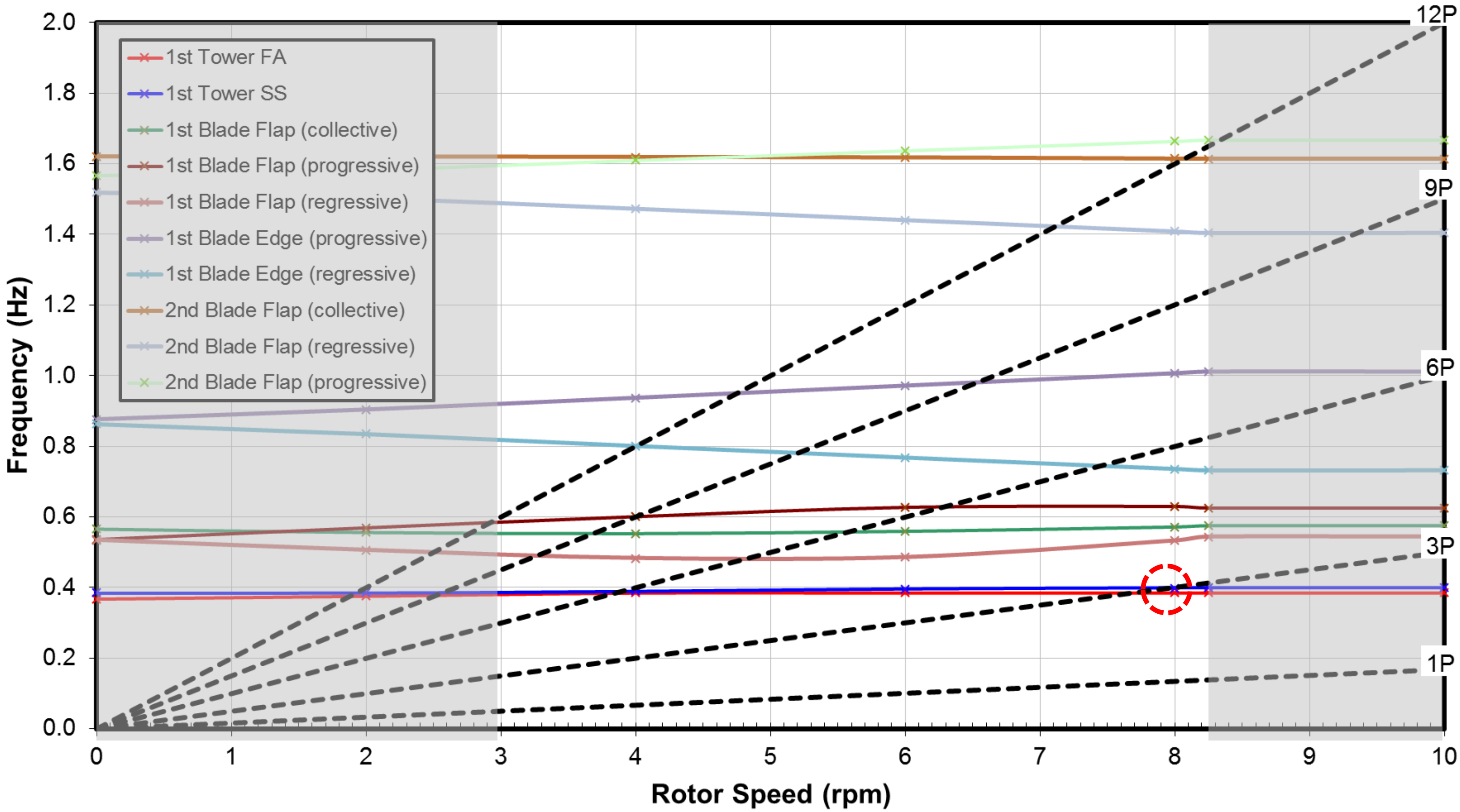






Campbell diagram (3P Issue)

Tower resonance
→ Need to redesign tower properties



Natural frequency of the tower

Example 1: mass on cantilever

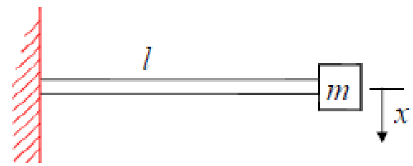
A machine of mass m is on light cantilevered bracket.

From 1.7.4, $k_{\text{eff}} = \frac{3EI}{l^3}$

$$m\ddot{x} = -k_{\text{eff}}\, x$$

$$m\ddot{x} + k_{\text{eff}}\, x = 0$$

$$m\ddot{x} + \frac{3EI}{l^3}\, x = 0 \quad \Rightarrow \quad \omega_n = \sqrt{\frac{3EI}{m\, l^3}}$$



Section shape	Area A, m²	Moment I, m⁴ (for bending)
h, b	bh	$\frac{bh^3}{12}$
2r	πr^2	$\frac{\pi}{4} r^4$
$2r_i$, $2r_o$, t	$\pi(r_o^2 - r_i^2) \approx 2\pi r t$	$\frac{\pi}{4}(r_o^4 - r_i^4) \approx \pi r^3 t$

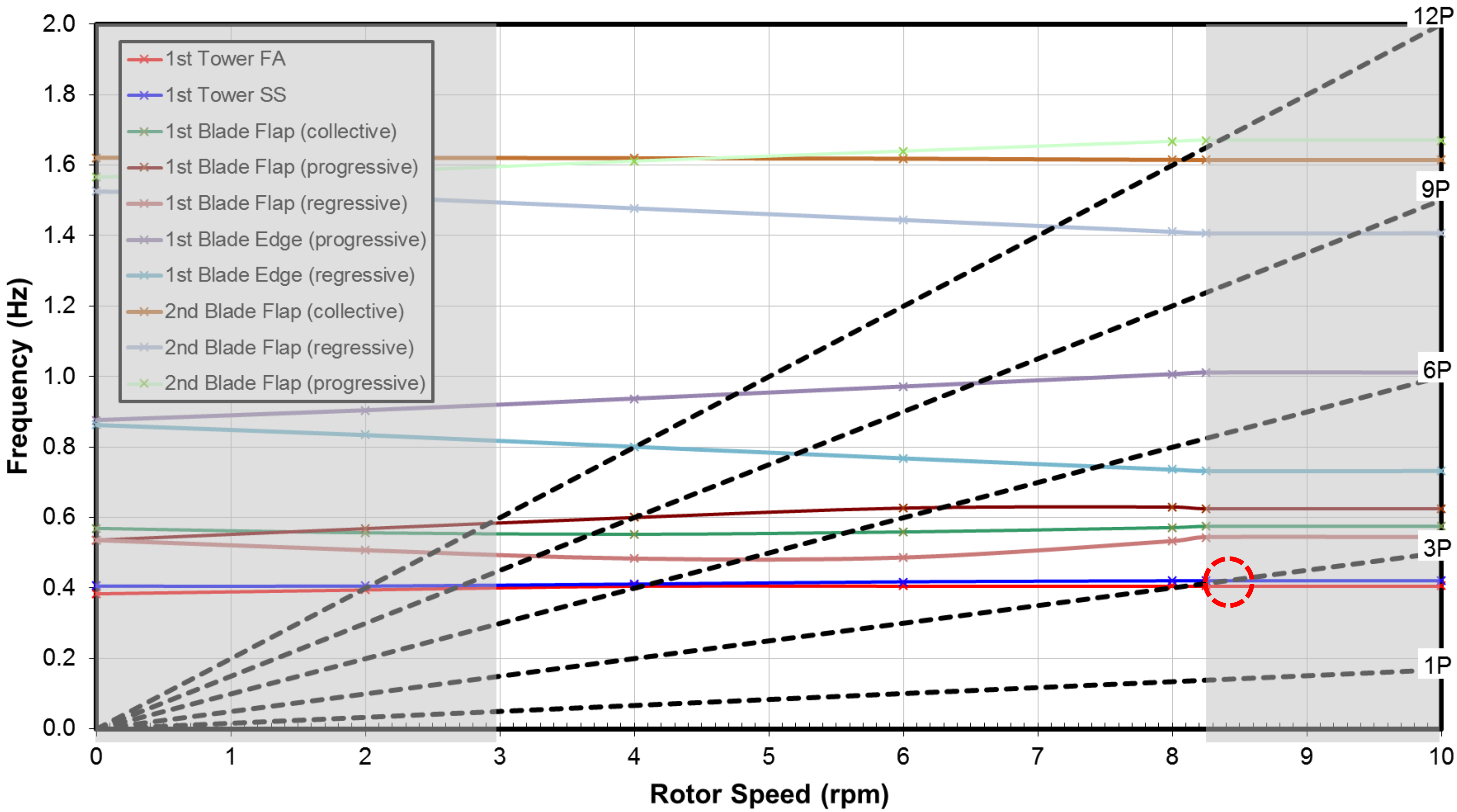
$$f_n = \frac{1}{2\pi}\sqrt{\frac{3E(\pi r^3 t)}{\left(\frac{33}{140} * \rho * 2\pi r t * l + M_{tophead}\right) l^3}} = C\sqrt{\frac{r^3}{l^3}} \propto \frac{D^{1.5}}{l^{1.5}}$$

- Rotor 3P-Excitation : 0.4125
- Tower 1st Side to Side Natural Frequency : 0.3982

Target	Tower Length
5% margin	104.84
2.5% margin	**106.53**
No margin	108.28

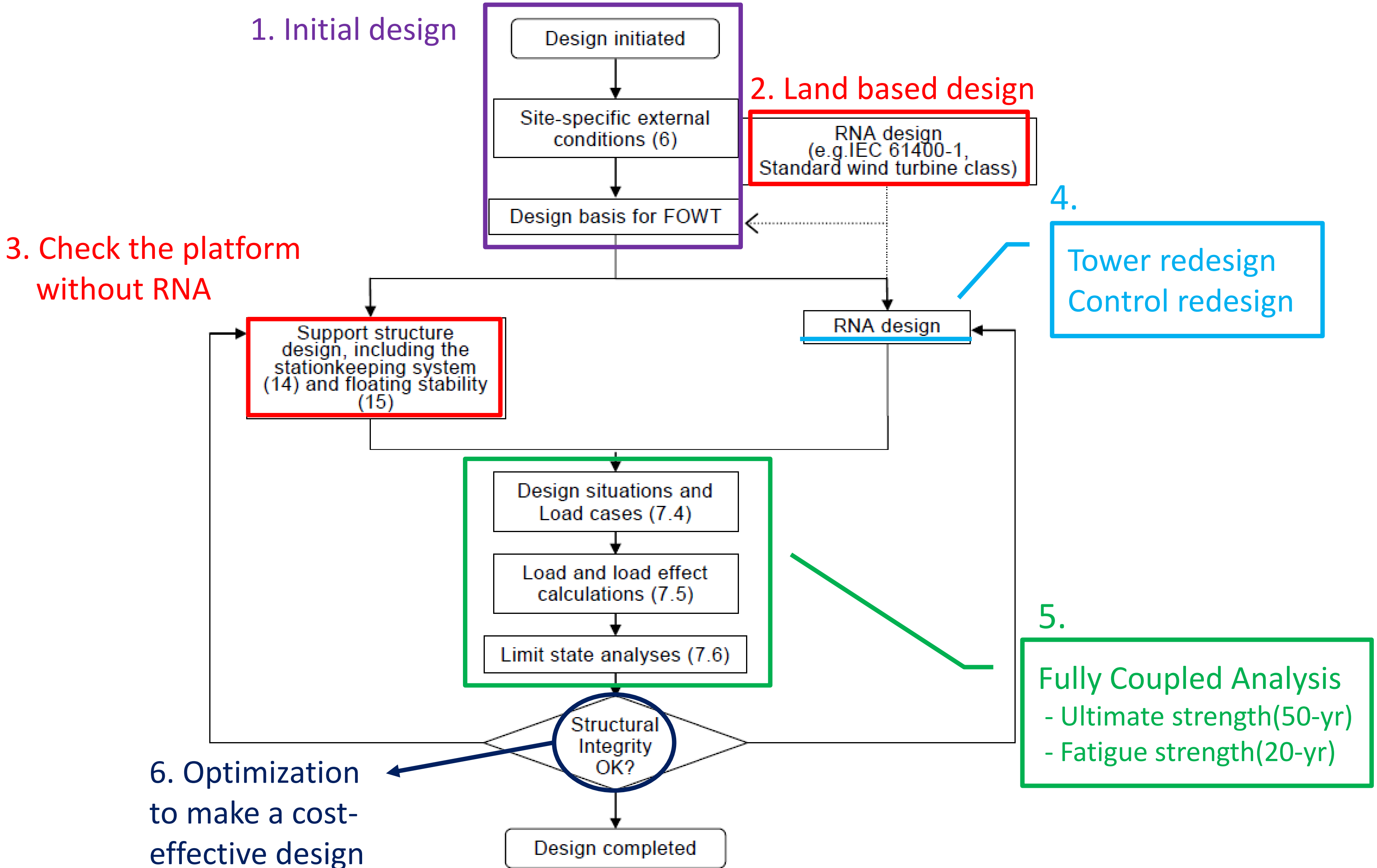
Campbell diagram(after)

Tower Length (to avoid 3P!!)
110.88 m → 106.53 m (-4.35m)



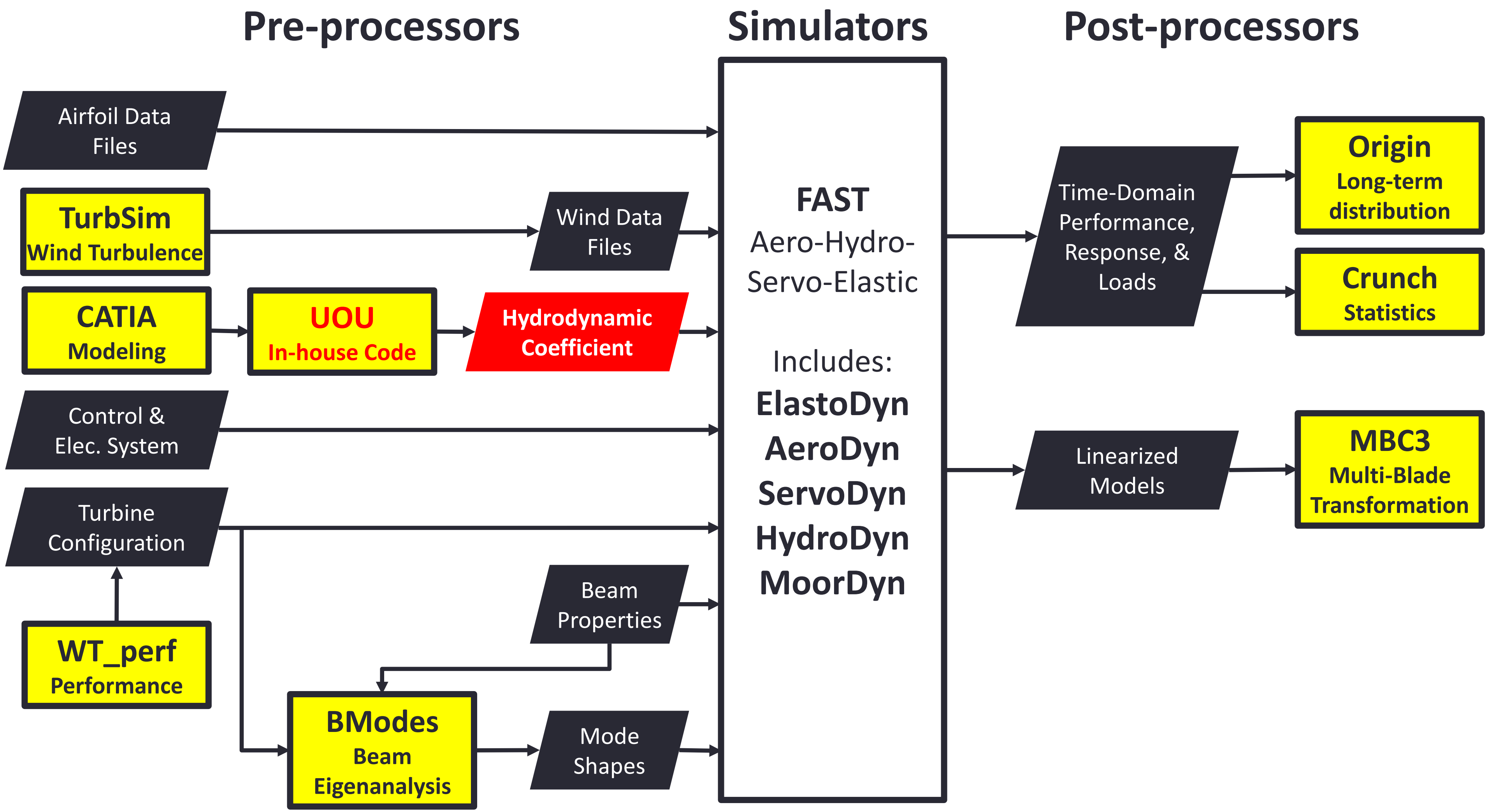
4. Numerical Simulation

Design process for a floating offshore wind turbine



Source: IEC61400-3-2

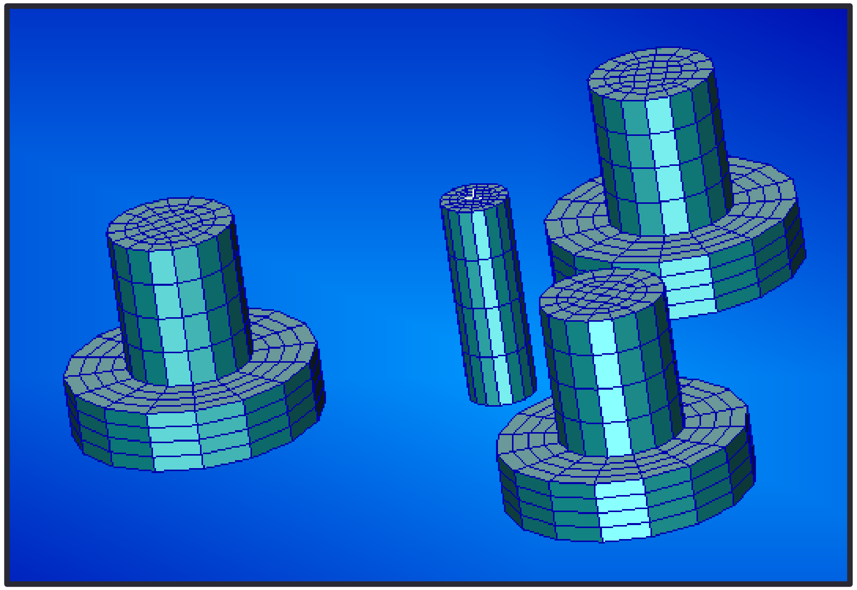
Flow Diagram of UOU + FAST v8



UOU in-house code

➢ **Hydrodynamic coefficients need for numerical simulation in hydro part**

Diffraction problem	+	Radiation problem	=	Motion equation

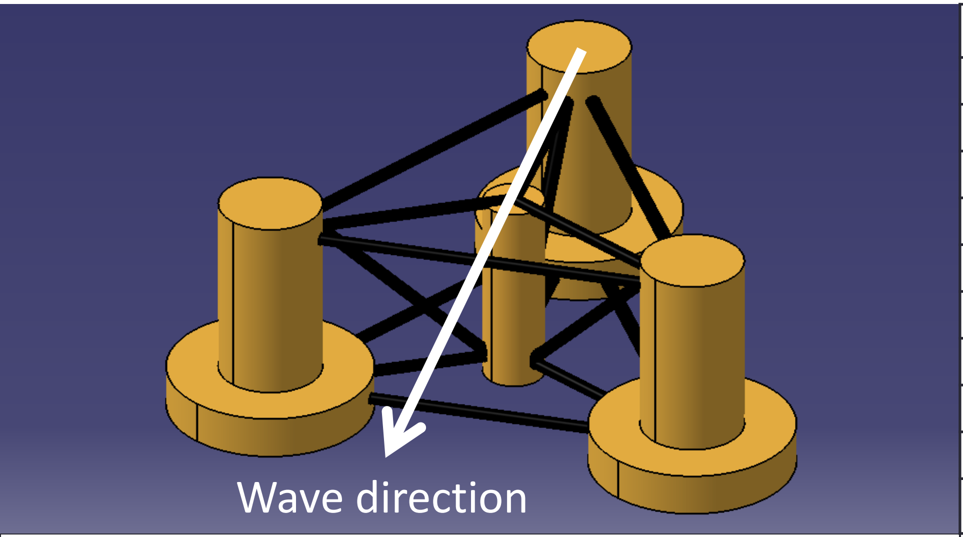


- **UOU in-house code**

3D panel method(BEM)
Element : 1024

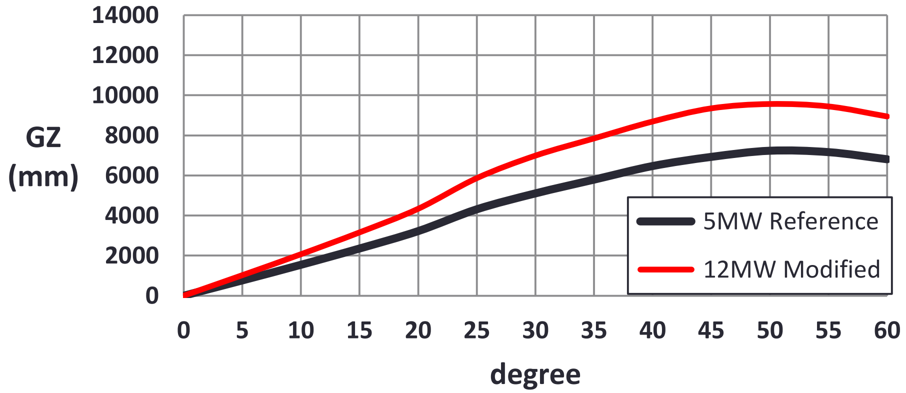
Output
1. Added mass coefficients
2. Radiation Damping coefficients
3. Wave Excitation Forces/Moments

12MW Stability analysis

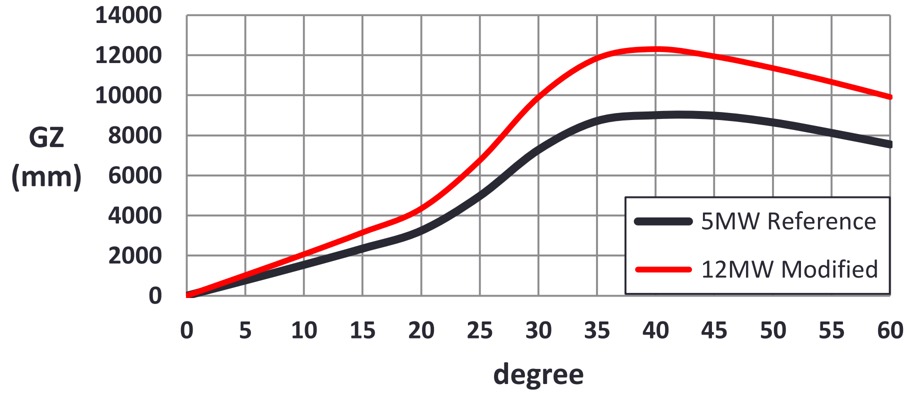


Floating Platform Geometry	5MW	12MW
Elevation of main column above SWL	10	10
Elevation of offset columns above SWL	12	16.215
Spacing between offset columns	50	67.562
Length of upper columns	26	35.132
Length of base columns	6	8.107
Depth to top of base columns below SWL	14	18.917
Diameter of main column	6.5	9.634
Diameter of offset (upper) columns	12	16.130
Diameter of base columns	24	32.260
Diameter of pontoons and cross braces	1.6	2.162

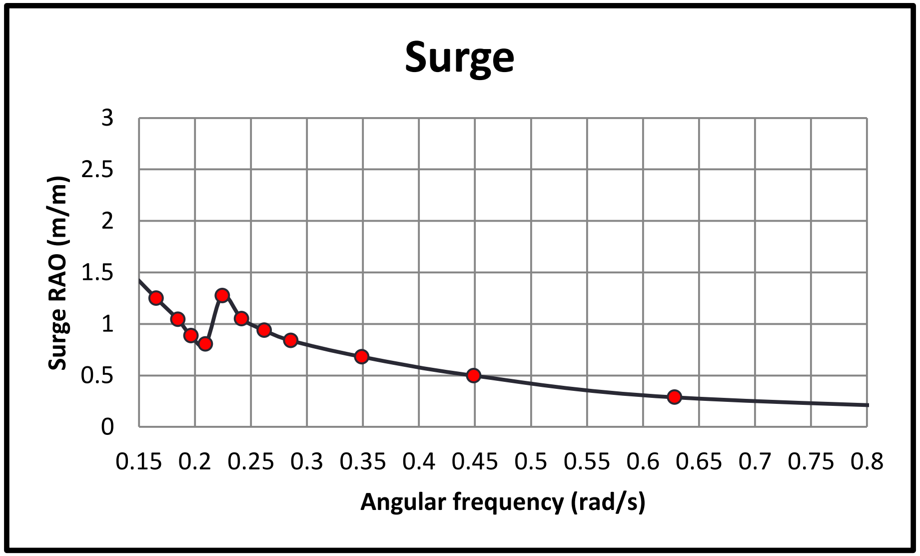
Transverse Stability (Roll)

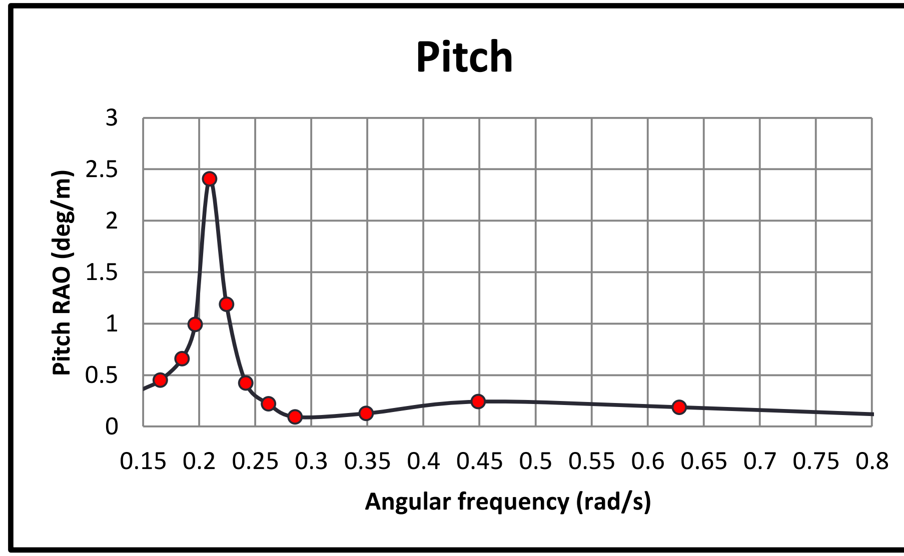


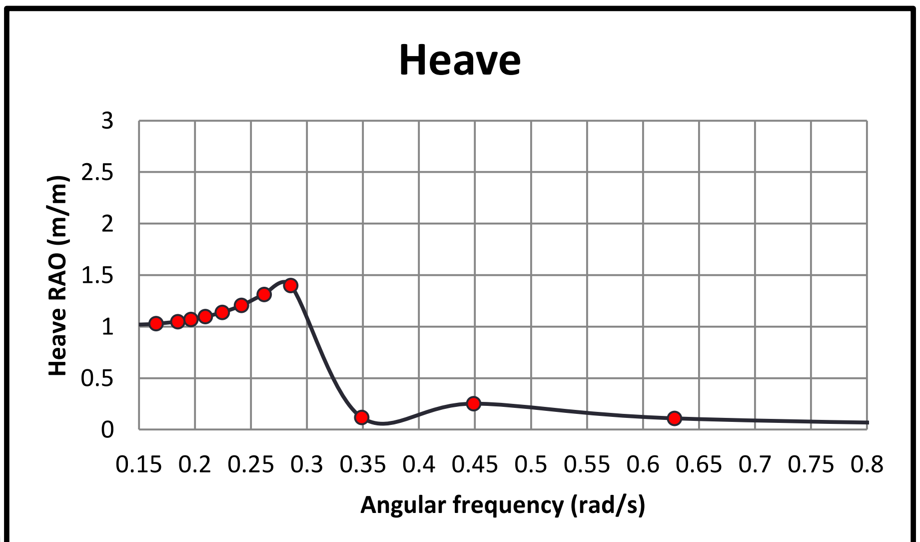
Longitudinal Stability (Pitch)



RAO results in regular wave







5. Design Load Cases(DLCs)

Design Load Cases

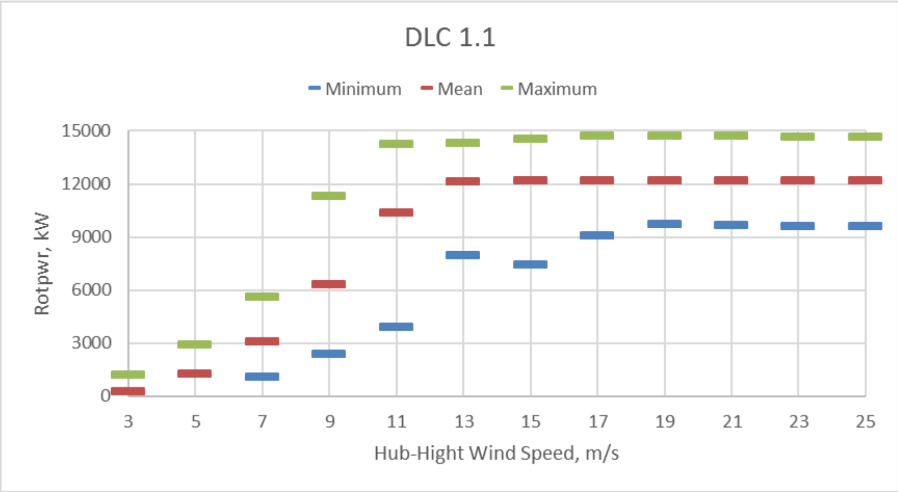
➢ IEC61400-3 : International Standards

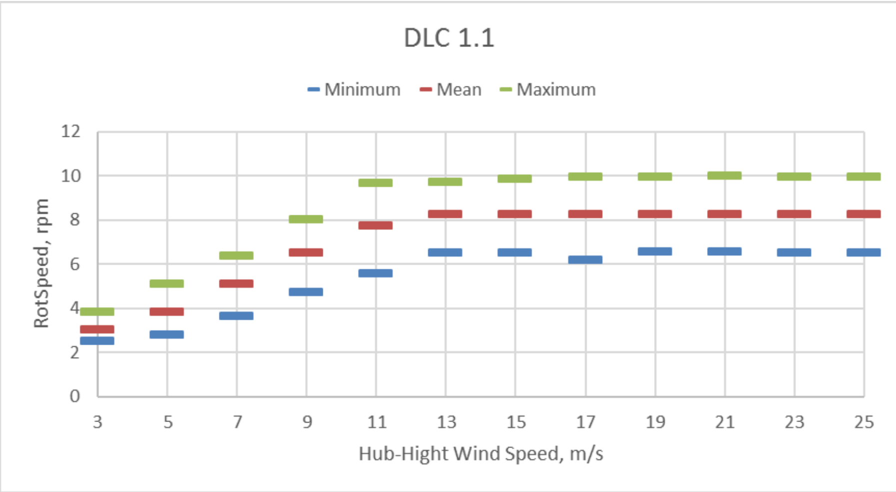
DLC	Significant Wave height	Peak Period	Wind Model
DLC1.1 (NSS)	3.2 m	9.6 s	NTM
DLC1.3 (NSS)	3.2 m	9.6 s	ETM
DLC1.6 (SSS)	9.72 m	13.98 s	NTM
DLC6.1 (ESS)	11.32 m	15.1 s	EWM50

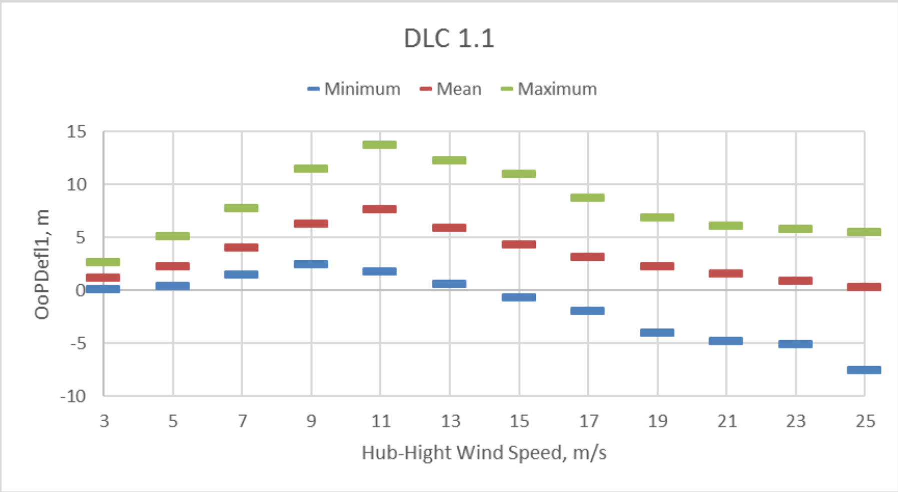
Preliminary study
for ultimate strength analysis
- DLC1.1
- DLC1.3
- DLC1.6
- DLC6.1

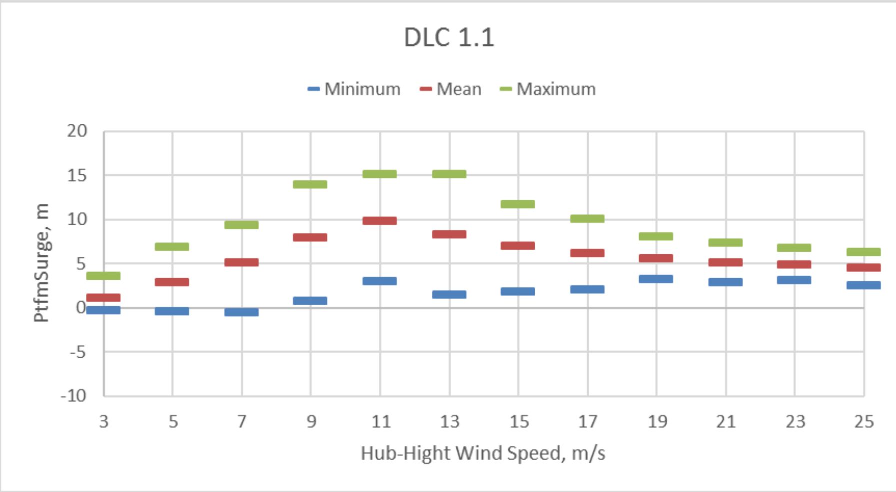
DLC1.1(NSS/NTM)

Normal **S**ea **S**tate : H_s = 3.2m / T_p = 9.6s
Normal **T**urbulence **M**odel : I_{ref} = 0.14(B)



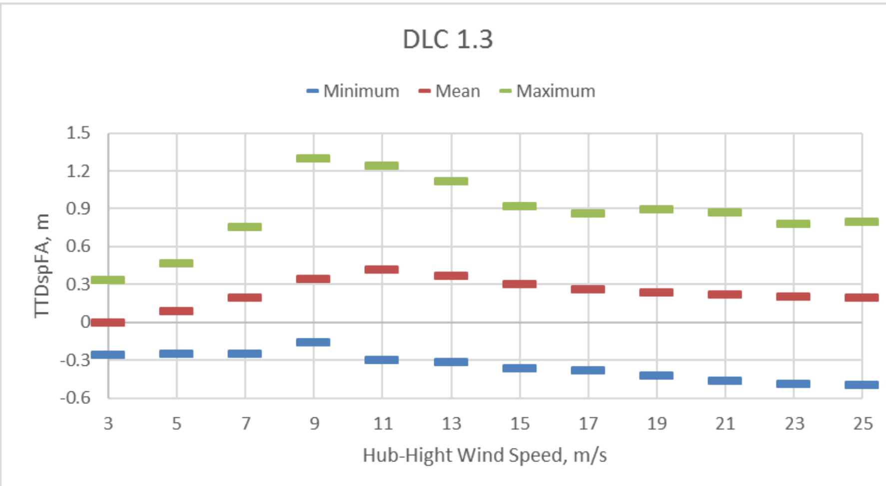


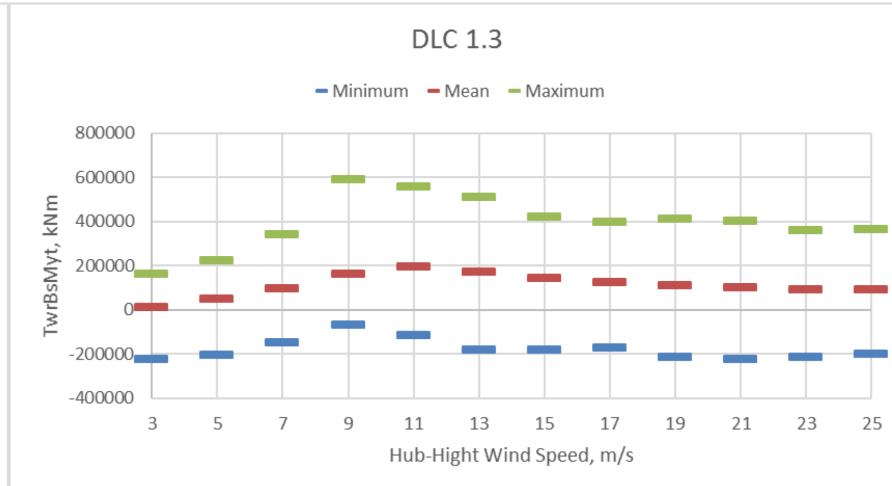


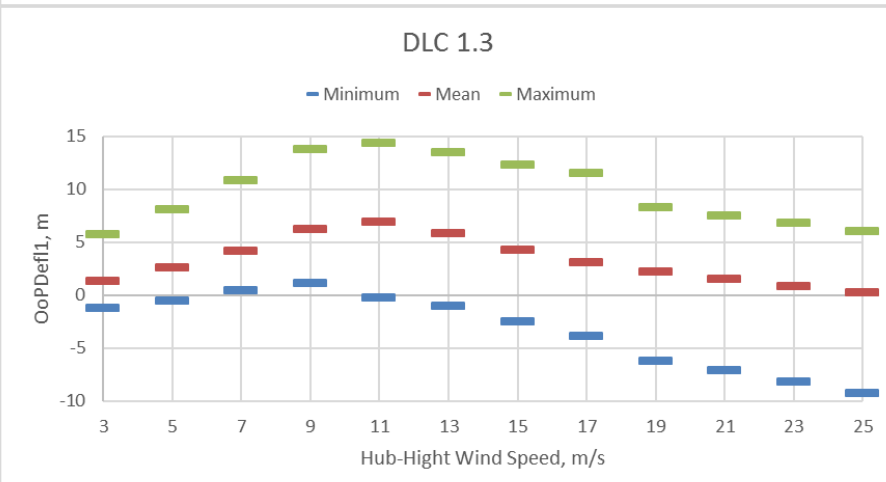


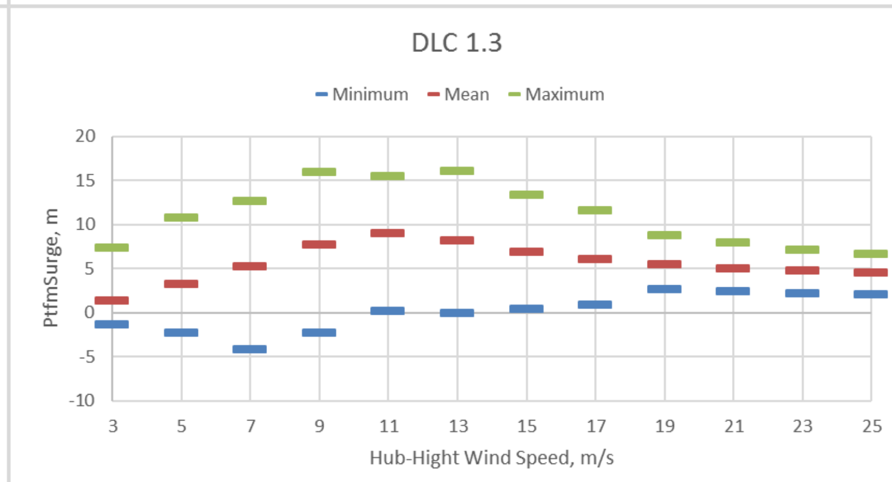
DLC1.3(NSS/ETM)

Normal **S**ea **S**tate : H_s = 3.2m / T_p = 9.6s
Extreme **T**urbulence **M**odel : I_{ref} = 0.14(B)



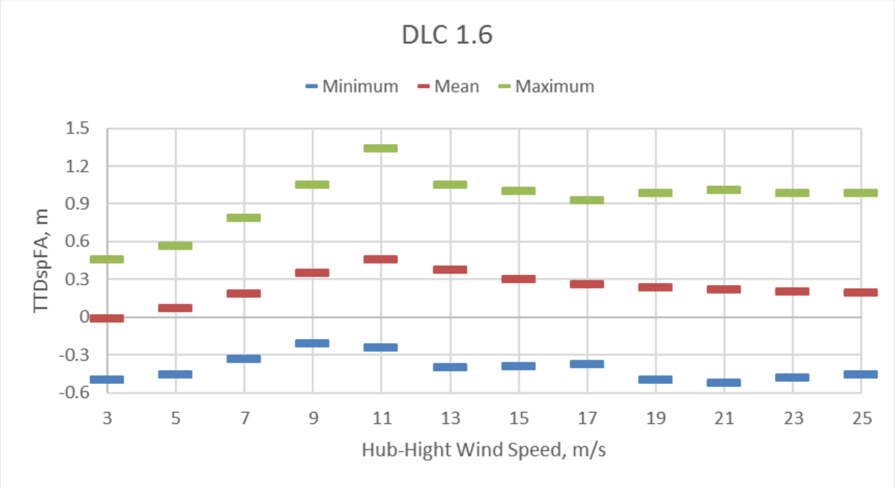


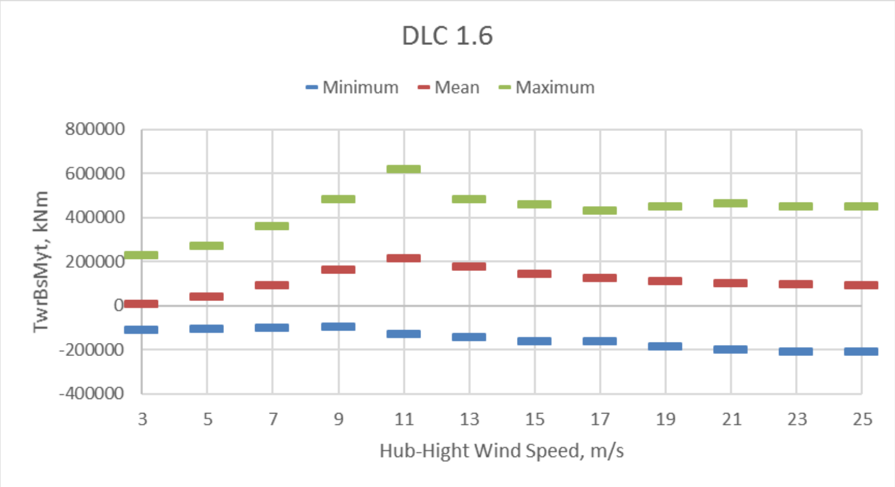


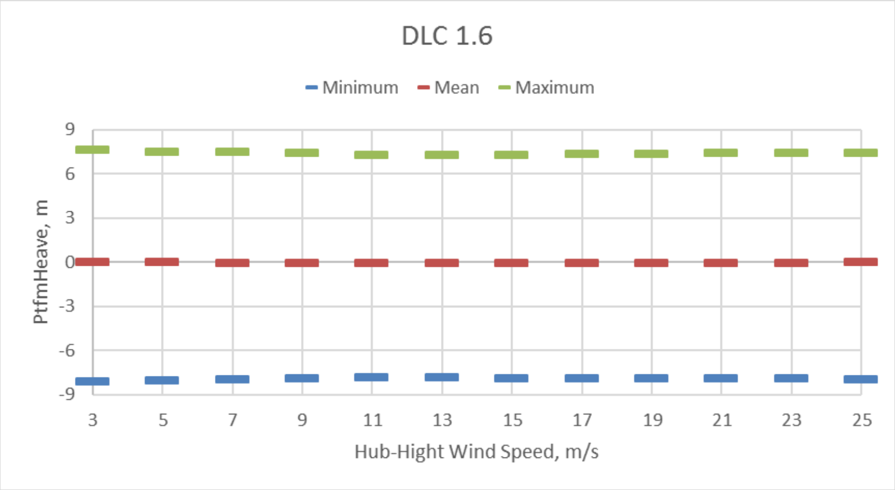


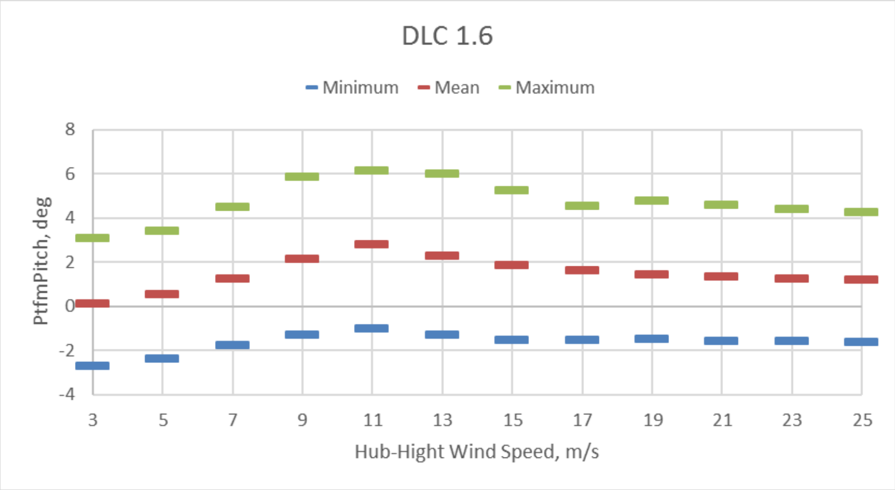
DLC1.6(SSS/NTM)

Severe **S**ea **S**tate : H_s = 9.72m / T_p = 13.98s
Normal **T**urbulence **M**odel : I_{ref} = 0.14(B)



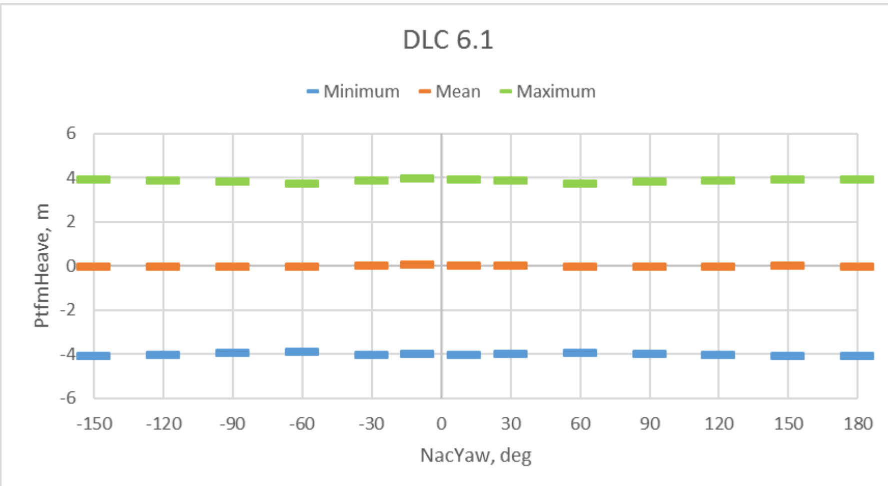


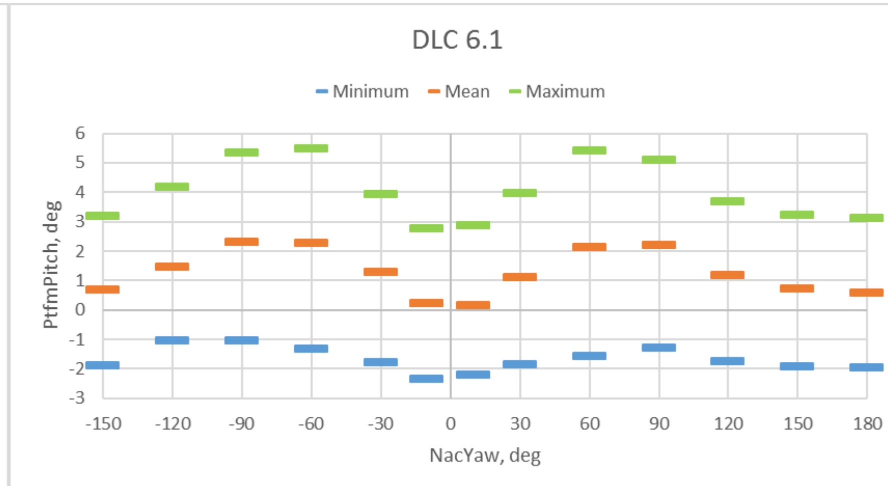


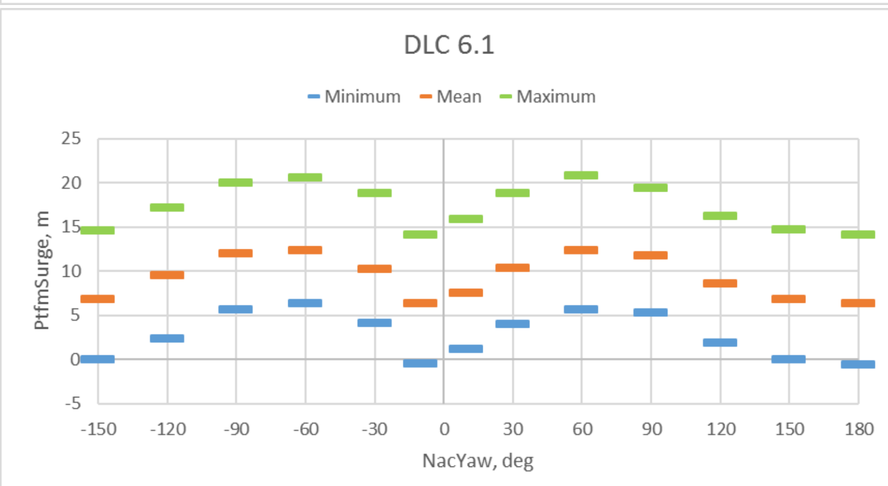


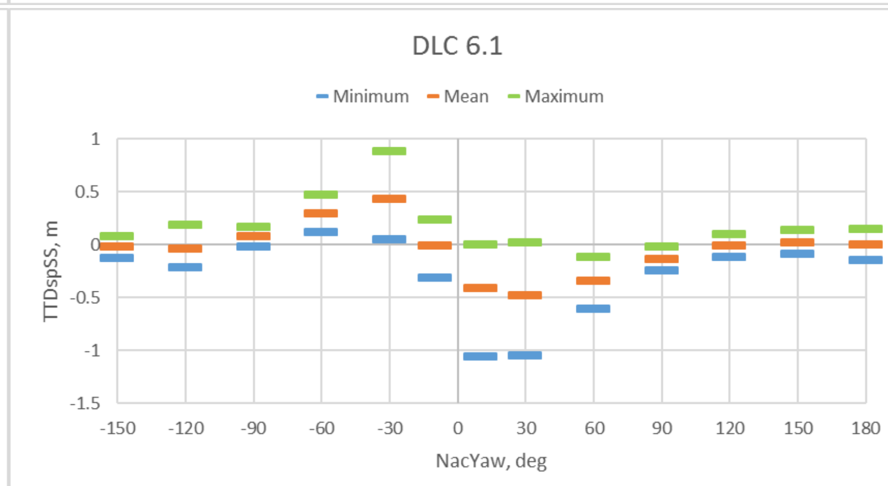
DLC6.1(ESS/EWM50)

Extreme **S**ea **S**tate : H_s = 11.32m / T_p = 15.1s
Extreme **W**ind Speed **M**odel : I_{ref} = 0.14(B)









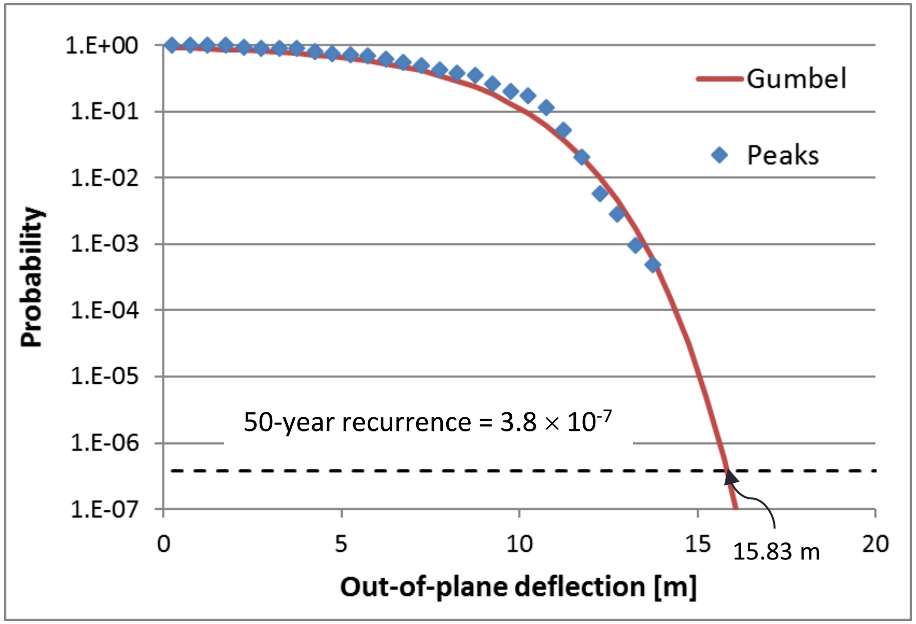
Summary

	Maximum	Units	DLC
Rotpwr	15,600.00	kW	DLC 1.6 (17 m/s)
GenPwr	15,370.00	kW	DLC 1.6 (17 m/s)
RotSpeed	10.56	rpm	DLC 1.6 (17 m/s)
OoPDefl1	14.33	m	DLC 1.3 (11 m/s)
TTDspFA	1.34	m	DLC 1.6 (11 m/s)
TTDspSS	0.88	m	DLC 6.1 (-30 deg)
TwrBsMyt	618,300.00	kNm	DLC 1.6 (11 m/s)
PtfmSurge	20.86	m	DLC 6.1 (+60 deg)
PtfmHeave	7.61	m	DLC 1.6 (3 m/s)
PtfmPitch	6.17	deg	DLC 1.6 (11.2 m/s)

Long-term distribution

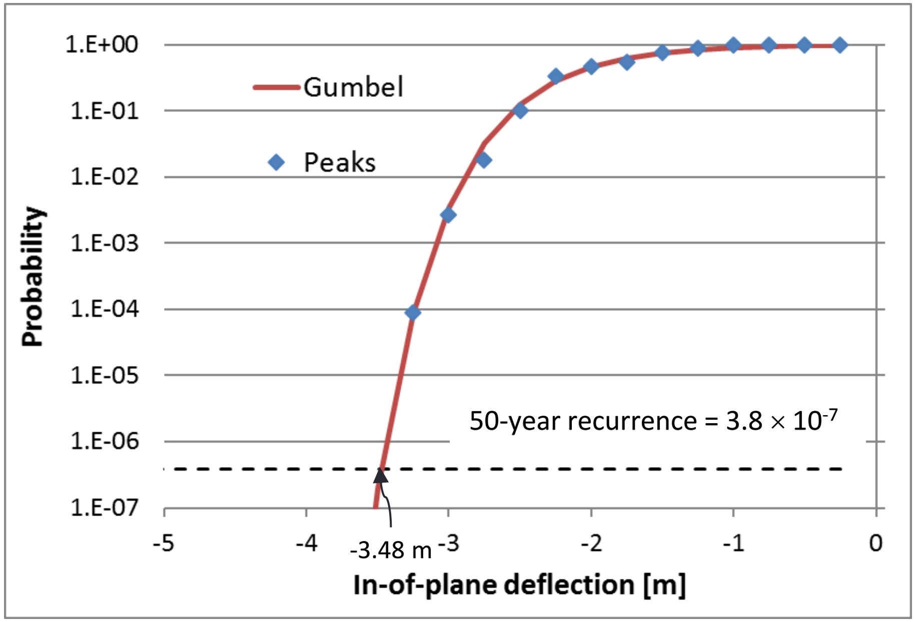
- IEC61400-1 Annex F
    - Statistical extrapolation of loads for ultimate strength analysis

Extrapolation of out-of-plane tip deflection



Out of plane tip Deflection
Extreme value 19.79 m
(safety factor 1.25)

Extrapolation of in-plane tip deflection



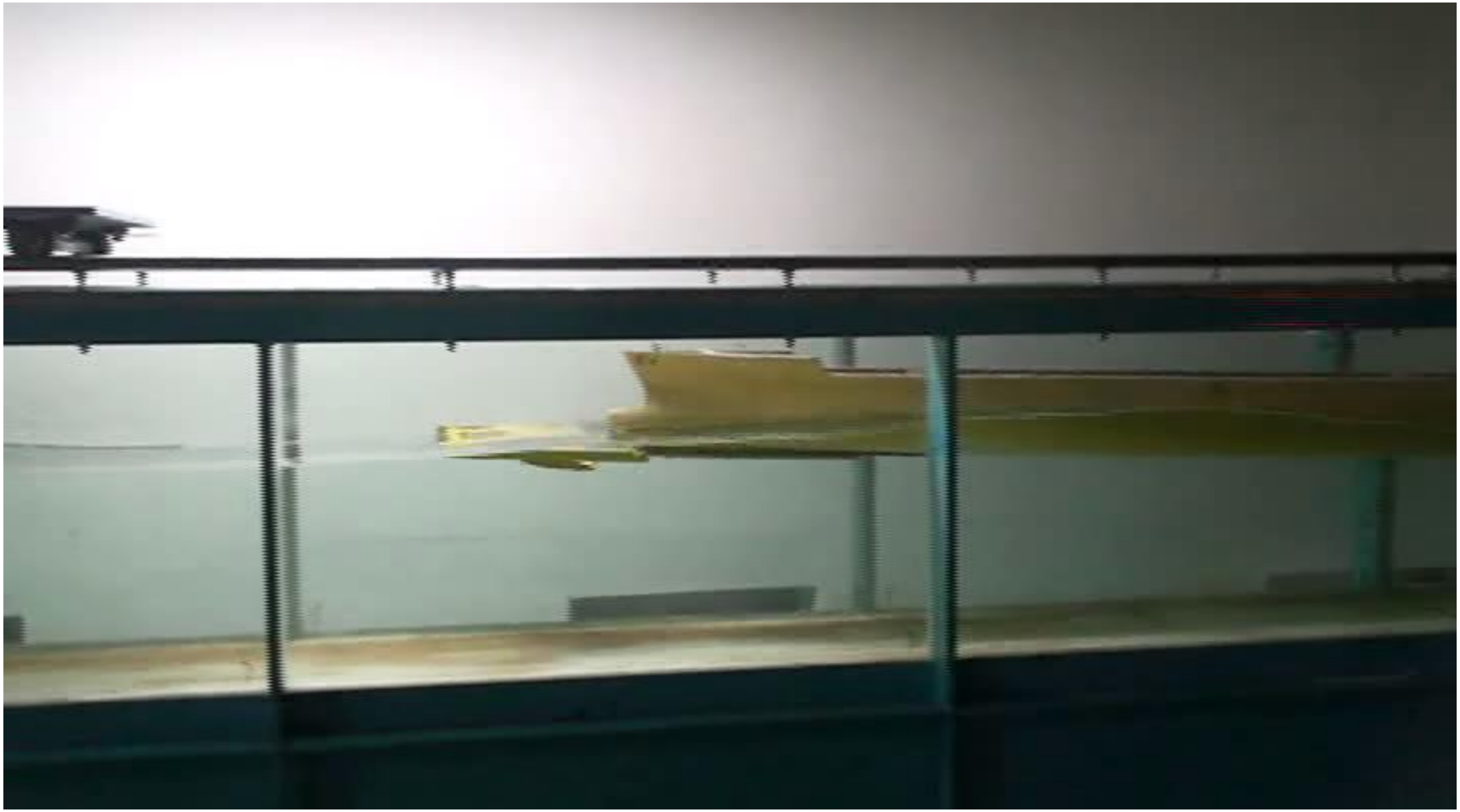
In plane tip Deflection
Extreme value -4.35 m
(safety factor 1.25)

5. Novel Offshore Floater

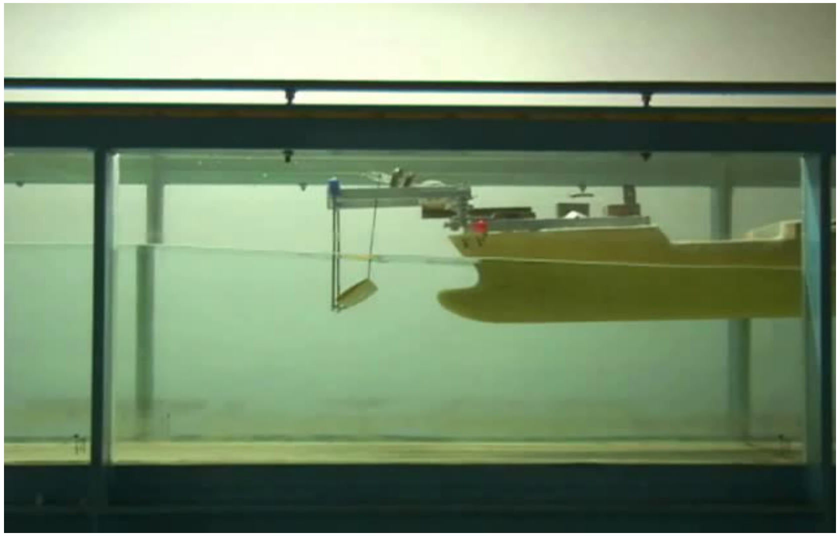
Wave Energy Propulsion

without foil	with foil
	

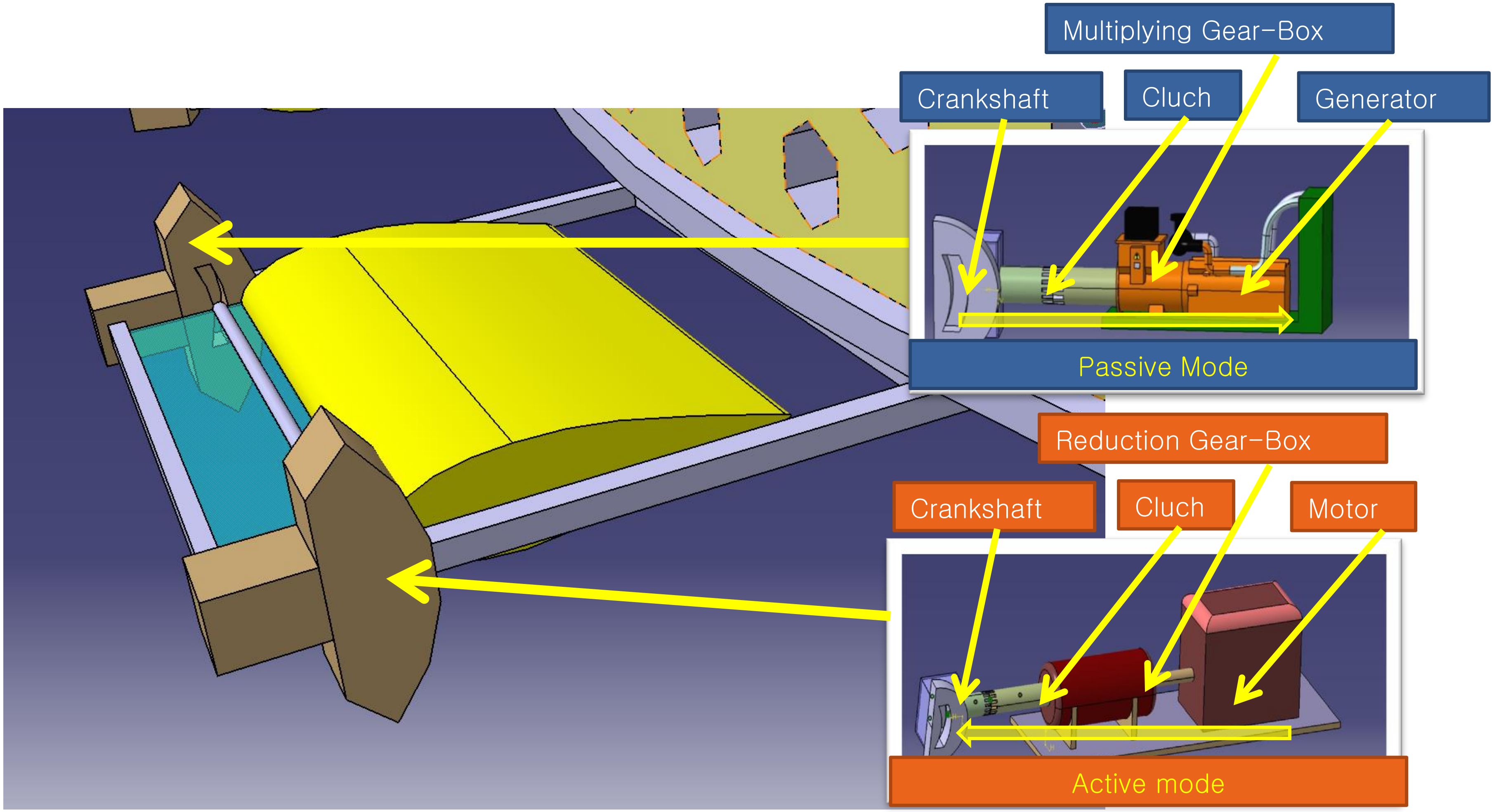
Wave Energy Propulsion



Wave Energy Propulsion



Passive/Active mode

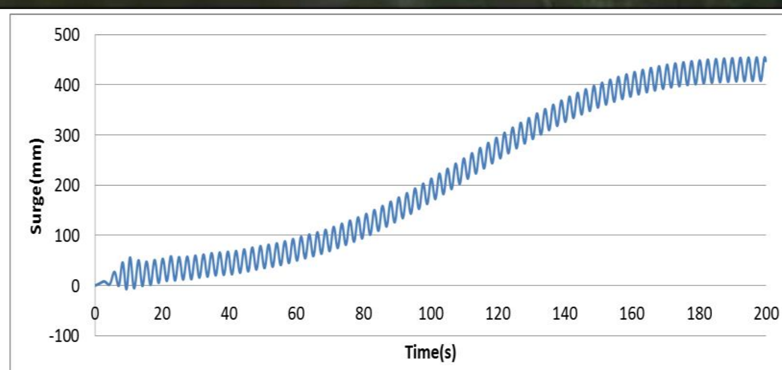


Novel Stationkeeping(passive mode)

Period : 2.43s, Wave Length : 9.18m, Wave Height : 0.075m, Frequency : 0.412Hz,

L wav / D : 10.2

Wave propagating direction



6. Conclusion

Conclusion

- **Preliminary design of a UOU 12MW floating offshore wind turbine is made by being scaled up from NREL 5MW wind turbine and OC4 semi-submersible.**
- **An innovative floater without mooring systems for the UOU 12MW FOWT is suggested.**
- **In order to reduce the top head mass, SCSG, Flexible shaft and CFRP blades are adopted in UOU 12MW FOWT.**
- **To avoid the negative damping of FOWTs, controller was modified.**
- **Tower length was changed to avoid the 3P excitation.**
- **Long term analysis of the UOU 12MW FOWT was performed.**
- **Later, IEC61400-3-2 rule should be considered for the UOU 12MW FOWT.**

THANK YOU!

ACKNOWLEDGMENTS

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