Analysis of the aerodynamic properties of an airfoil in an offshore setting

MAE 441/579: Wind Energy
Dr. Ronald Calhoun

By :
Kenneth Dmello, Ayush Kumar Singh & Gaurav Ashwin Chandavarkar

Why Offshore ??

- **Offshore wind turbines generate more energy due to stronger winds and improved efficiency.**
- **They do not take up valuable land and have less visual impact than onshore turbines.**
- **Offshore wind farms can be located farther from populated areas, reducing noise pollution and potential health impacts.**
- **Offshore wind farms provide habitat for marine life and support recreational activities.**

Cont…,

- Offshore wind technology is becoming more cost-effective and can create jobs and stimulate economic growth.
- Offshore wind farms reduce greenhouse gas emissions and improve energy grid resilience.
- They can help countries meet renewable energy goals and transition away from fossil fuels.
- Offshore wind farms can also contribute to national security by reducing reliance on imported energy sources.

Europe Data

- **Almost half of the active companies in the wind sector (onshore and offshore) are headquartered in the EU. To explore offshore sites further out to sea with stronger and more consistent winds, several European developers are working on floating offshore wind turbines.**

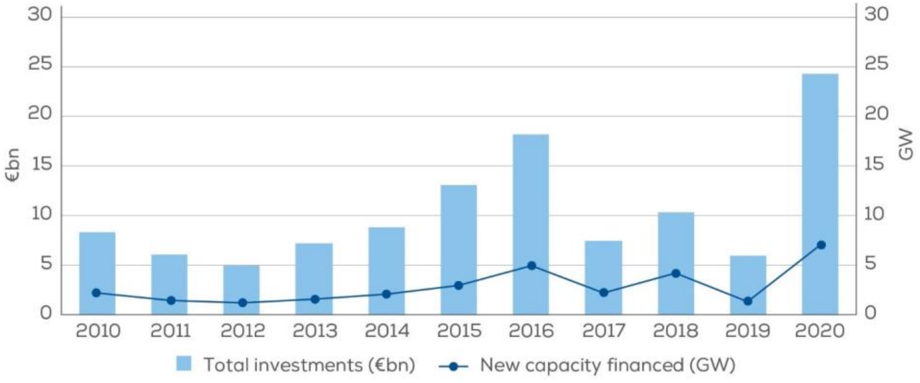
- **The deployment of offshore wind energy is at the core of delivering the European Green Deal. The installed offshore wind capacity in the EU was 14.6 GW in 2021 and is set to increase by at least 25 times by 2030, using the vast potential of the 5 EU sea basins.**

- **The strategy sets targets for an installed capacity of at least 60 GW of offshore wind by 2030, and 300 GW by 2050.**

- **Europe now has a total installed offshore wind capacity of 25 GW. That corresponds to 5,402 grid-connected wind turbines across 12 countries**

FIGURE 18

New offshore wind investments and capacity financed: 2010 – 2020 (€bn)

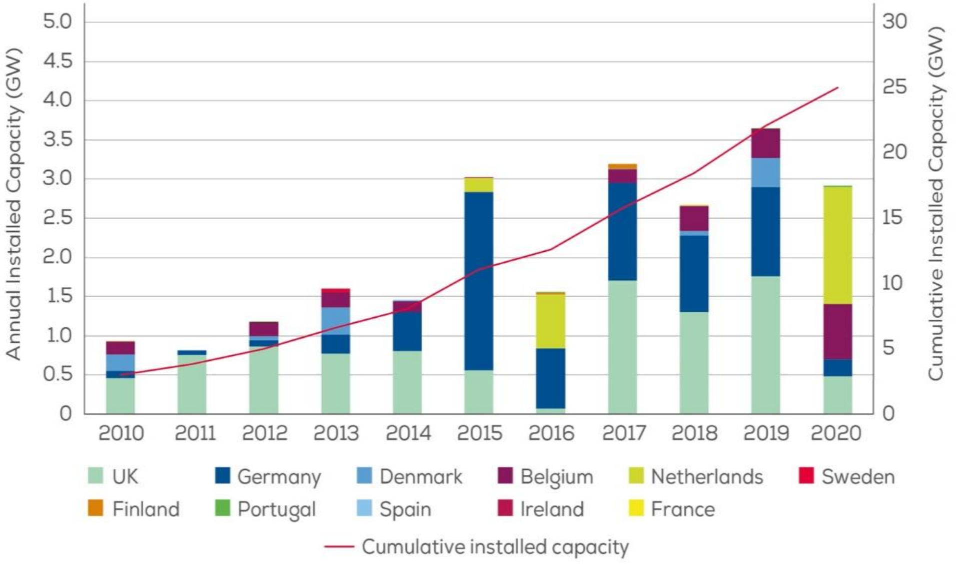


	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Total investments (€bn)	8.4	6.1	5	7.2	8.8	13.1	18.2	7.5	10.3	6	24.2
New capacity financed (GW)	2.2	1.5	1.3	1.6	2.1	3	5	2.3	4.2	1.4	7.1

Source: WindEurope

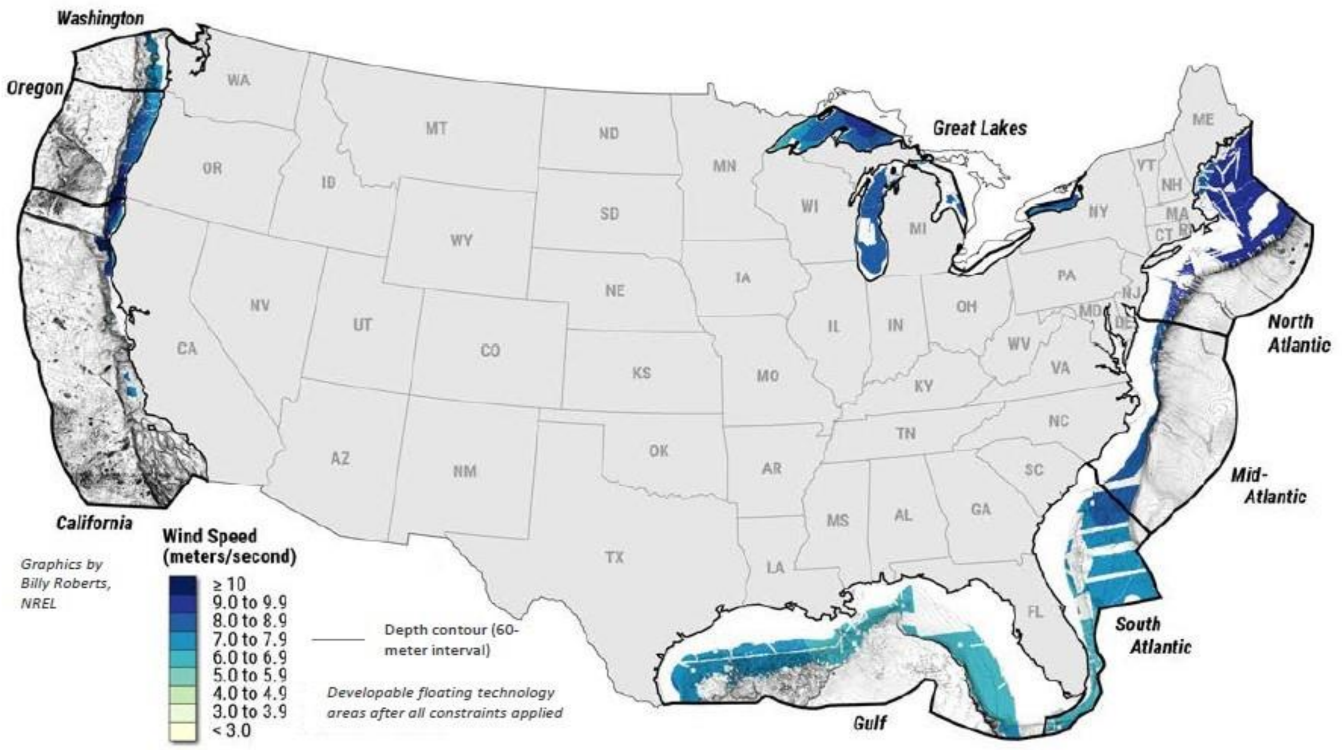
FIGURE 1

Annual offshore wind installations by country (left axis) and cumulative capacity (right axis)



Source: WindEurope

Floating OSW Energy Technology Technical Potential (Open Access)

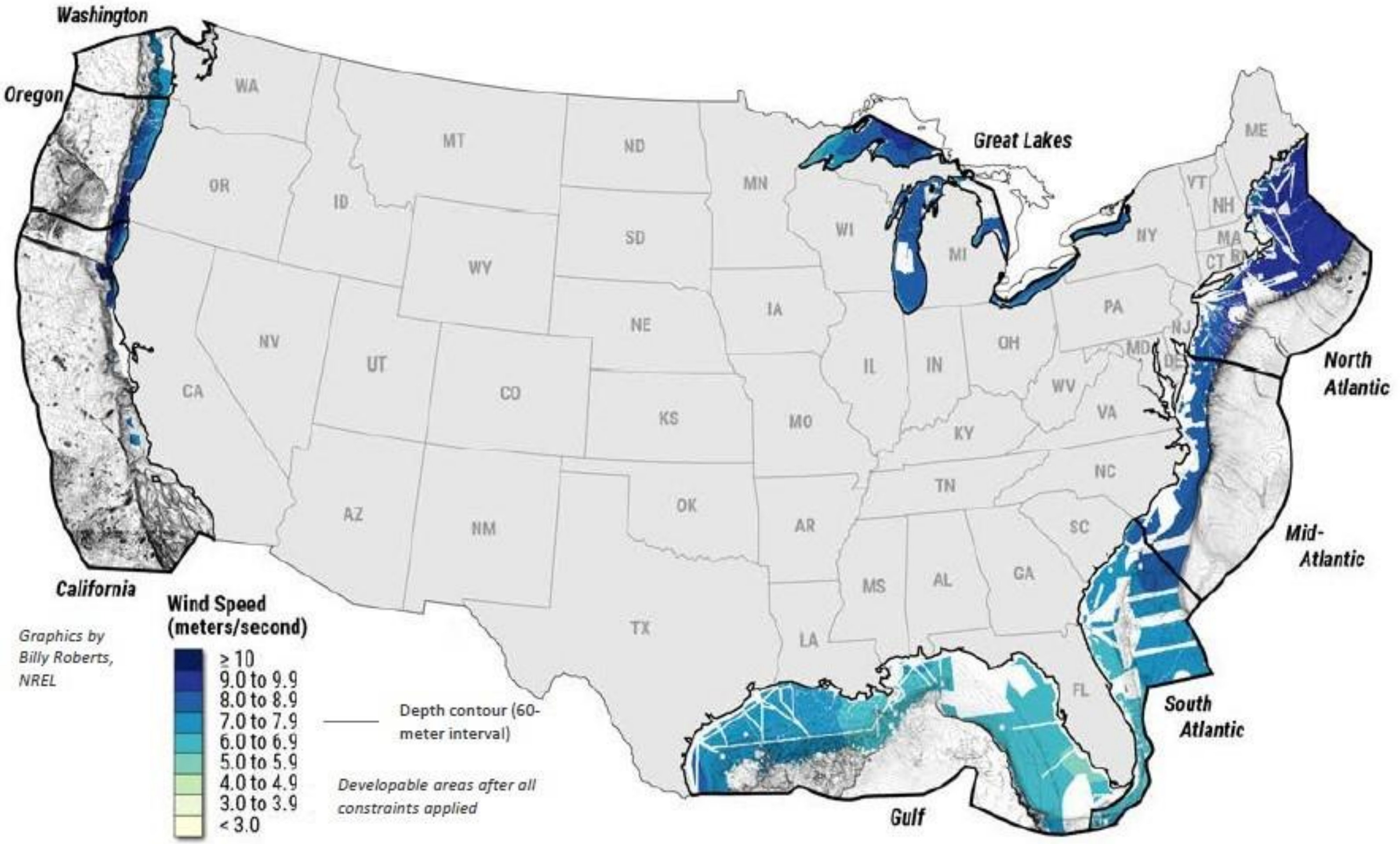


Region	GW	TWh
California	88	338
Great Lakes	415	1,535
Gulf	867	2,289
Mid Atlantic	166	607
North Atlantic	442	1,843
Oregon	150	544
South Atlantic	586	1,628
Washington	59	188
CONUS Total	**2,773**	**8,972**

*values are rounded to closest integer

- **In the United States, OSW energy is at a more nascent stage with only seven turbines, totaling 42 megawatts (MW), installed through 2021. Over 40 gigawatts (GW) of OSW energy capacity are at various stages of development as of 2021.**
- **Eighteen projects in the U.S. offshore pipeline have reached the permitting phase, and eight states have set their own offshore wind energy procurement goals, which total 40 GW by 2040.**

Total OSW Energy Technical Capacity Potential (Open Access)



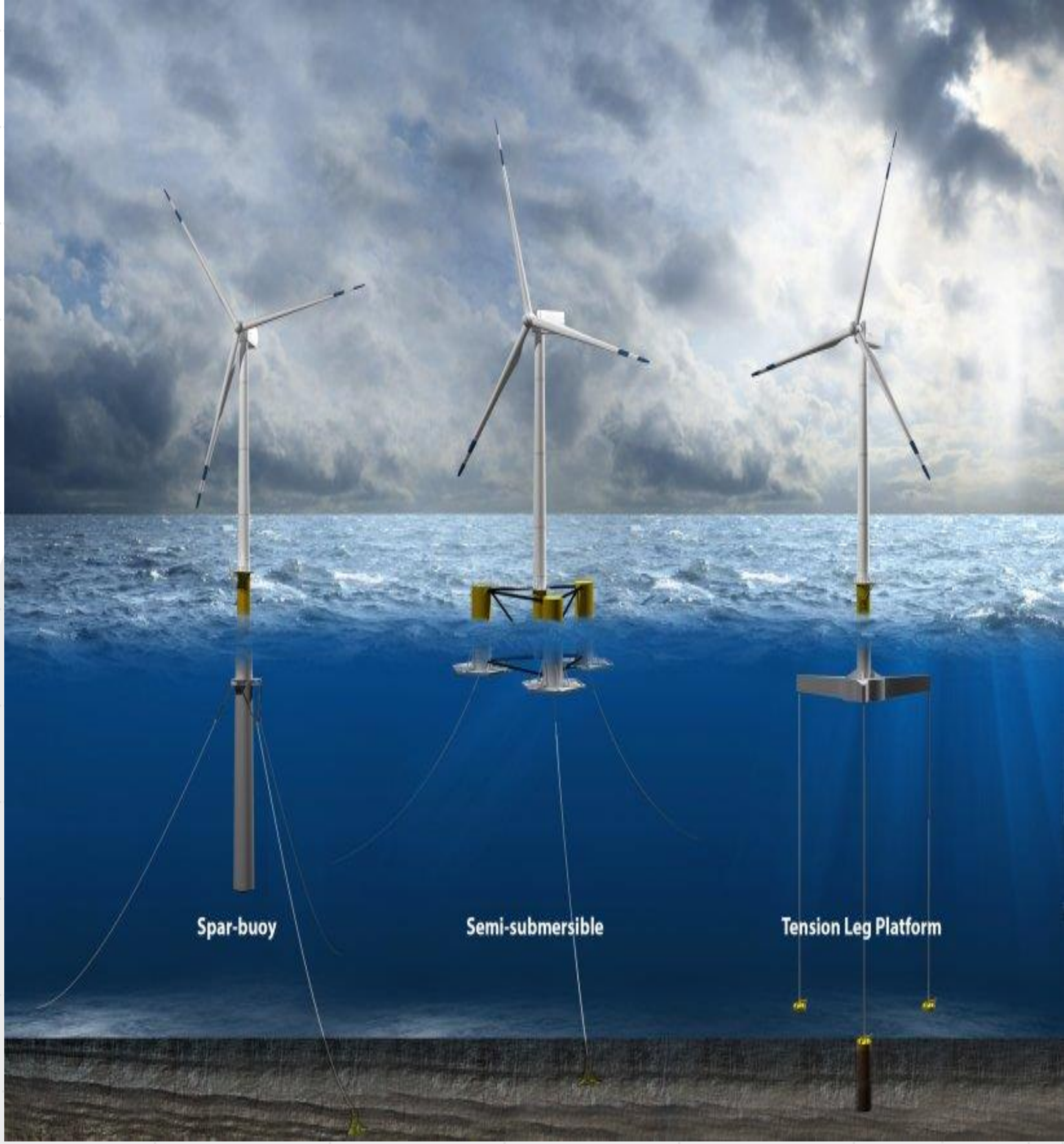
Region	Fixed-Bottom (GW)	Floating (GW)	Fixed-Bottom (%)	Floating (%)
California	4	88	4	96
Great Lakes	160	415	28	72
Gulf	696	867	45	55
Mid-Atlantic	157	166	49	51
North Atlantic	264	442	37	63
Oregon	2	150	1	99
South Atlantic	188	586	24	76
Washington	5	59	8	92
CONUS Total	**1,476**	**2,773**	35	65

*values are rounded to closest integer

Note: DOD-defined wind exclusion areas constitute an area equivalent to an additional 428 GW of California OSW wind energy potential.

Types of offshore floating mountings

- **Spar :** This type achieves system stability with the help of ballast installed below the main buoyancy tank to maintain a proper centre of buoyancy.
- **Semisubmersible :** Achieves static stability by distributing buoyancy widely at the water surface level. Easier to transport and setup at site.
- **Tension Leg Platform:** Stability is achieved by mooring lines attached to a submerged buoyancy tank

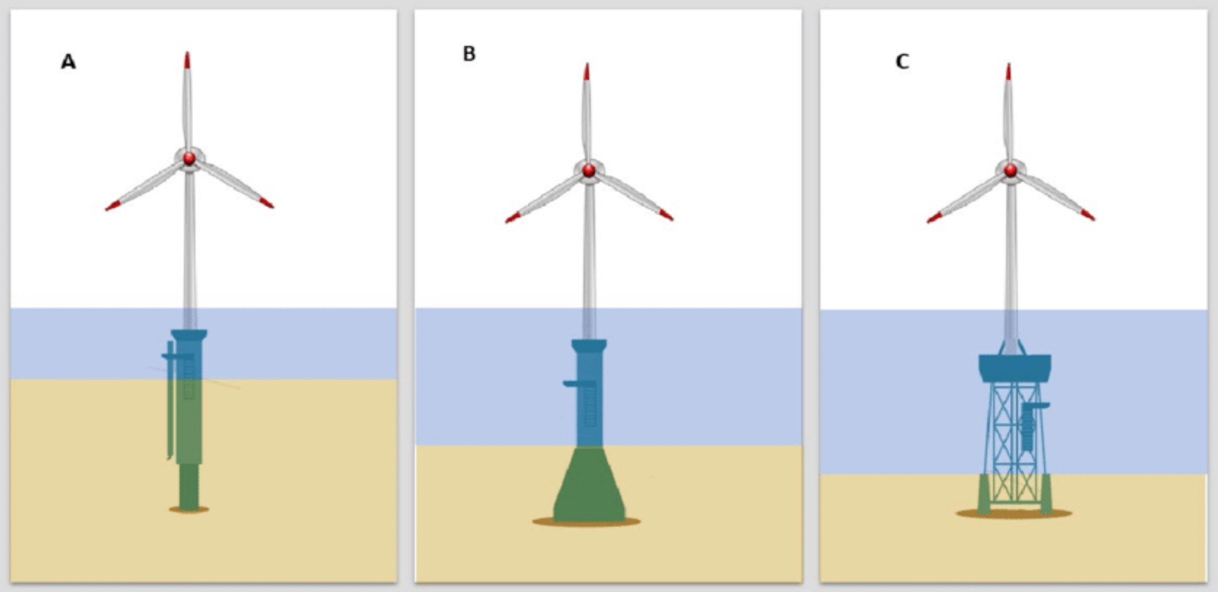


Types of fixed offshore mountings

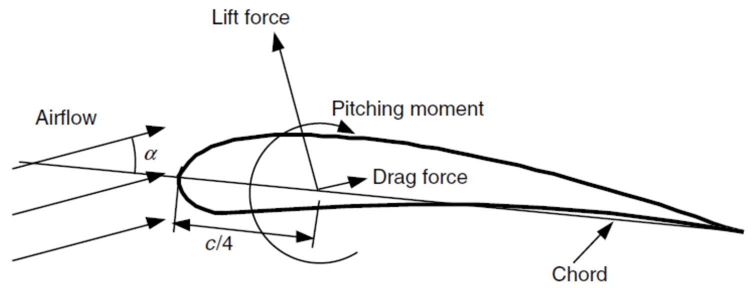
- **Monopile Foundations(A):** Can be used to depths to 40 m. They are a common choice for offshore turbines located in shallow water (less than 35 m). Cost-effective for installations to 40 m. Have a simple design that installs quickly.

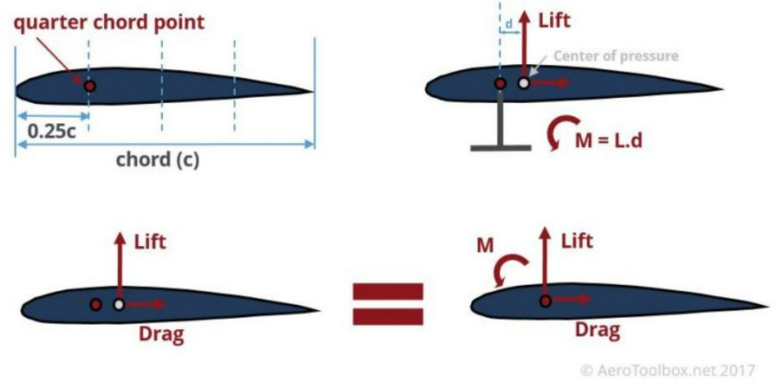
- **Gravity-Based Foundations(B):** Suitable for sites to depths up to 30 m. Some designs do not need crane installation. Tugboats can move port-assembled floated-to-fixed GBFs into place, reducing costs and risk.

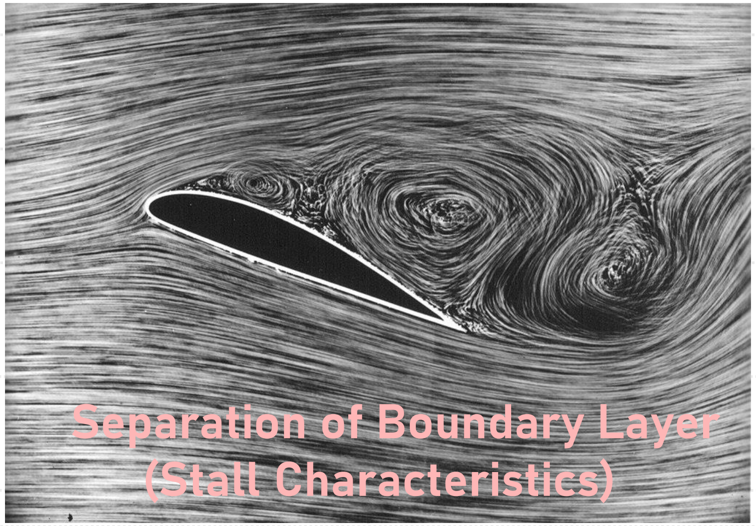
- **Jacket Foundations(C):** Can be installed to depths of 60 m. Can be installed using piles or suction caissons in stiff clays or medium-to-dense sands. Economical choice using straightforward manufacturing methods.



Airfoils







Separation of Boundary Layer (Stall Characteristics)

Two-dimensional Lift coefficient

$$C_l = \frac{L/l}{\frac{1}{2}\rho U^2 c} = \frac{\text{Lift force/unit length}}{\text{Dynamic force/unit length}}$$

Two-dimensional Drag coefficient

$$C_d = \frac{D/l}{\frac{1}{2}\rho U^2 c} = \frac{\text{Drag force/unit length}}{\text{Dynamic force/unit length}}$$

Pitching moment coefficient

$$C_m = \frac{M}{\frac{1}{2}\rho U^2 A c} = \frac{\text{Pitching moment}}{\text{Dynamic moment}}$$

Angle of relative Wind= Section pitch angle +Angle of Attack

$$\varphi = \theta_p + \alpha$$

Incremental force normal to plane of rotation (aerodynamic loading).

$$\mathrm{d}F_N = \mathrm{d}F_L \cos\varphi + \mathrm{d}F_D \sin\varphi$$

Tanngential force to plane of rotation (contributes in torque).

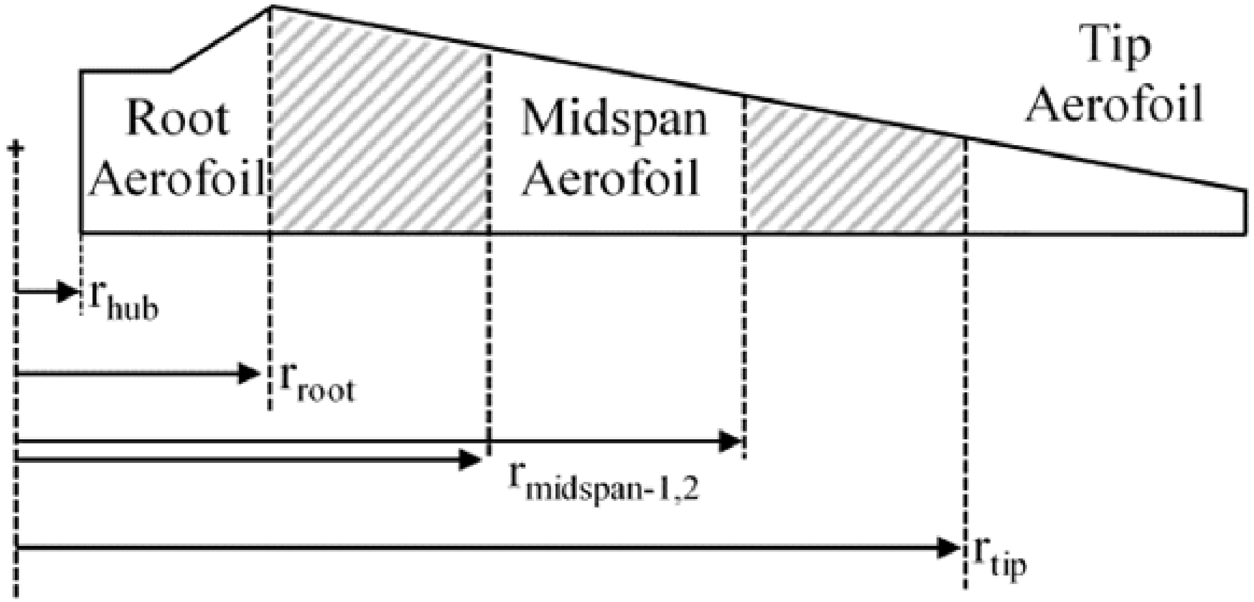
$$\mathrm{d}F_T = \mathrm{d}F_L \sin\varphi - \mathrm{d}F_D \cos\varphi$$

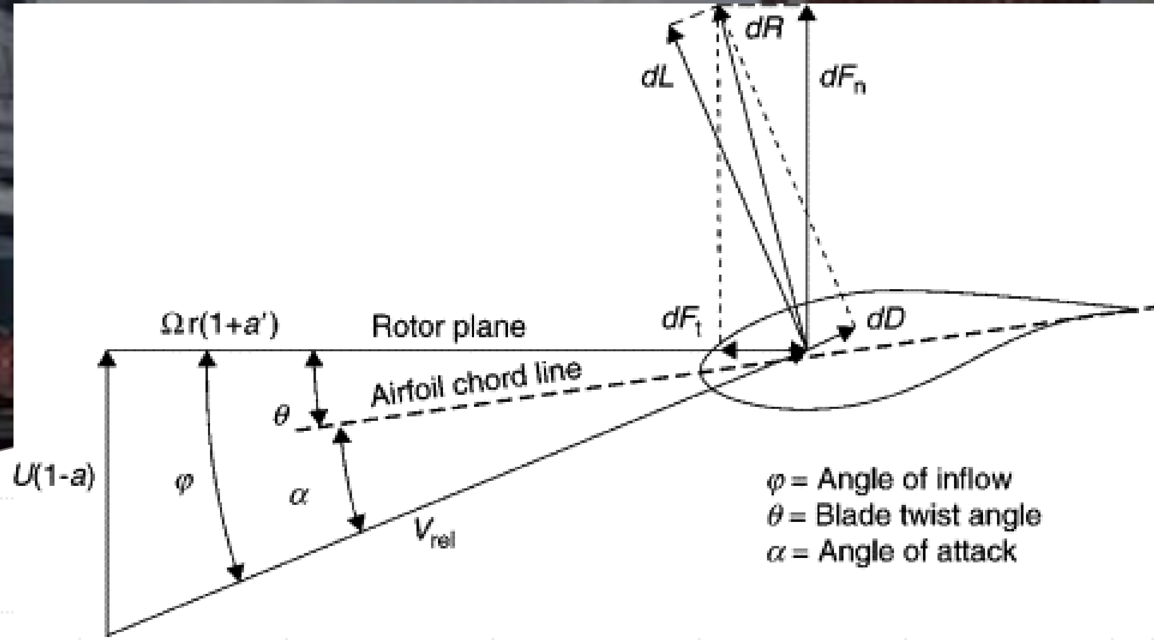
Force and Torque acting on a section at a distance r and with 3 rotor blades.

$$\mathrm{d}F_N = B\tfrac{1}{2}\rho U_{rel}^2 (C_l \cos\varphi + C_d \sin\varphi) c\,dr$$

$$\mathrm{d}Q = B\tfrac{1}{2}\rho U_{rel}^2 (C_l \sin\varphi - C_d \cos\varphi) c\,r\,dr$$

Why Blade is Twisted??





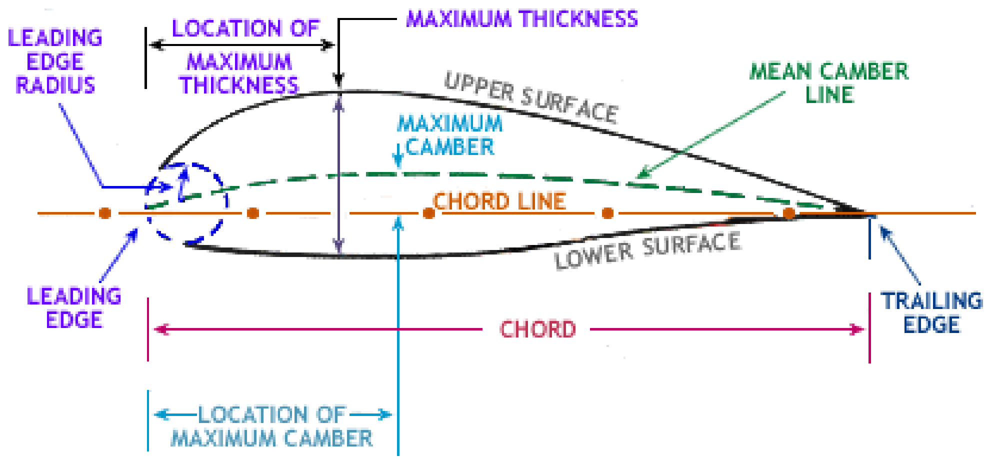
NACA 4-digit airfoil specification

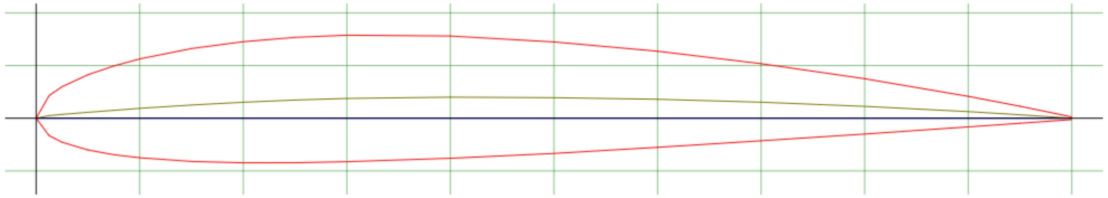
This NACA airfoil series is controlled by 4 digits e.g. NACA 2412, which designate the camber, position of the maximum camber and thickness. If an airfoil number is

NACA MPXX

NACA 2412

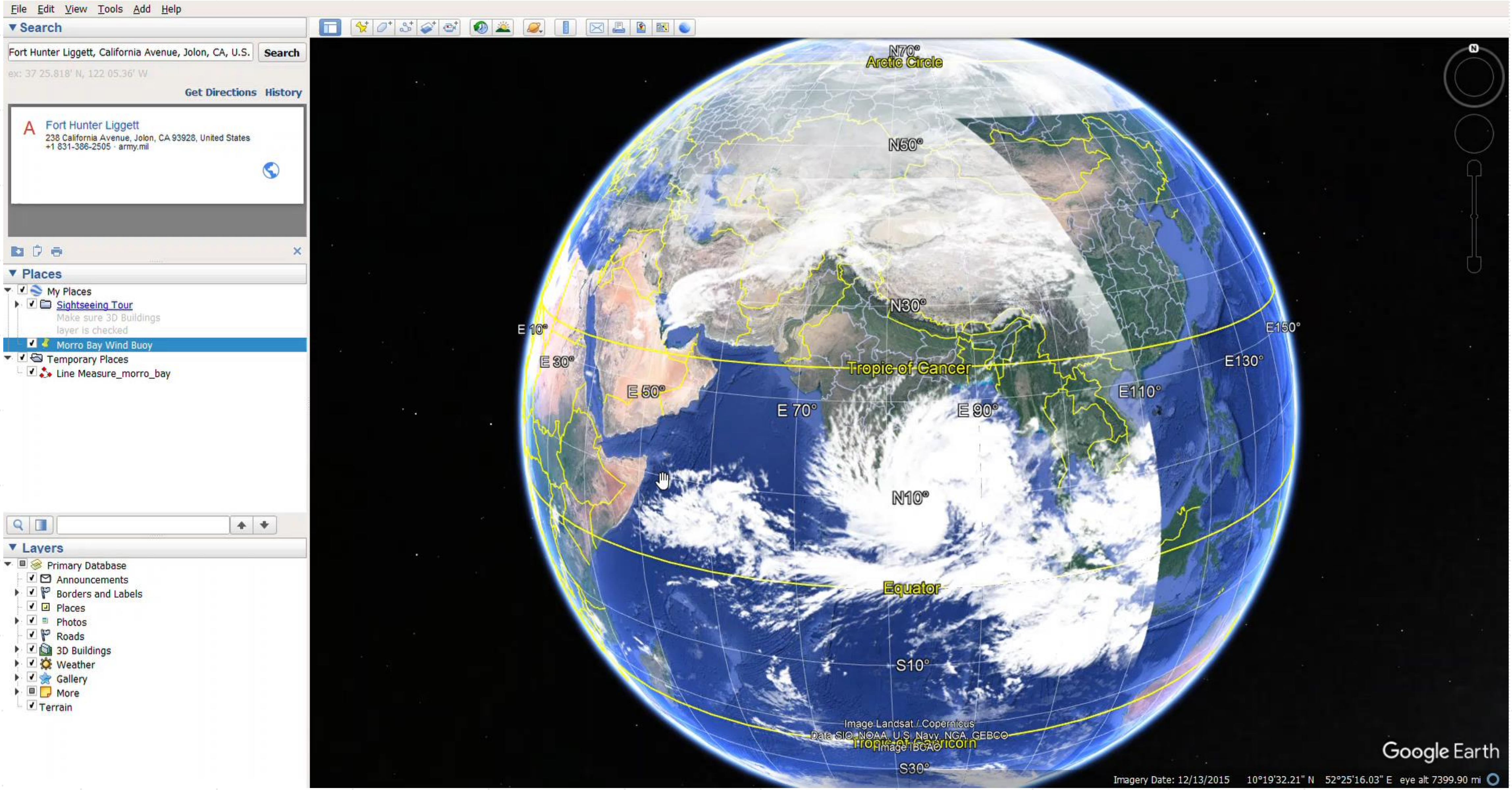
- M is the maximum camber divided by 100. In the example M=2 so the camber is 0.02 or 2% of the chord
- P is the position of the maximum camber divided by 10. In the example P=4 so the maximum camber is at 0.4 or 40% of the chord.
- XX is the thickness divided by 100. In the example XX=12 so the thickness is 0.12 or 12% of the chord.



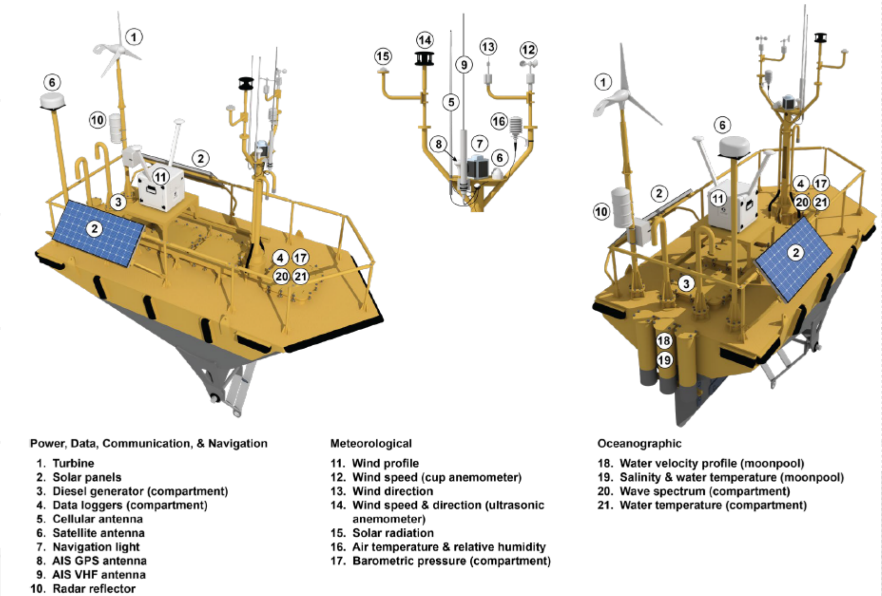


NACA 2412 airfoil

Morro Bay


File Edit View Tools Add Help
Search
Fort Hunter Liggett, California Avenue, Jolon, CA, U.S.
Search
ex: 37 25.818' N, 122 05.36' W
Get Directions History
Fort Hunter Liggett
238 California Avenue, Jolon, CA 93928, United States
+1 831-386-2505 · army.mil
Places
My Places
Sightseeing Tour
Make sure 3D Buildings layer is checked
Morro Bay Wind Buoy
Temporary Places
Line Measure_morro_bay
Layers
Primary Database
Announcements
Borders and Labels
Places
Photos
Roads
3D Buildings
Weather
Gallery
More
Terrain
N70°
Arctic Circle
N50°
N30°
Tropic of Cancer
N10°
Equator
S10°
S30°
Tropic of Capricorn
E 10°
E 30°
E 50°
E 70°
E 90°
E110°
E130°
E150°
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
Google Earth
Imagery Date: 12/13/2015 10°19'32.21" N 52°25'16.03" E eye alt 7399.90 mi

Data processing



- Modified code from HW3 to retrieve horizontal velocities for Morro Bay which were in a NetCDF file.
- Data included horizontal velocities for 457 days in 144 directions at 12 range rings.
- Processed NaN values and calculated mean velocities over all range rings.
- 12 range rings from a height of 40m to 250m

max_velocity.m | code_final.m | data_extract.m | new_file.m

```
vars_to_load =  {'wind_speed', 'wind_direction', 'time'};
projectdir = '/MATLAB Drive/Wind Energy/Project';
info = dir( fullfile(projectdir, '*.nc') );
n_files = length(info);
filenames = fullfile( projectdir, {info.name} );
lat = cell(n_files,1);
lon = cell(n_files,1);
series = cell(n_files, 1);
time= cell(n_files,1);
for k = 1 : n_files
  f = filenames{k};
  wind_velocity{k} = ncread(f, vars_to_load{1});
  wind_direction{k} = ncread(f, vars_to_load{2});
  time{k} = ncread(f, vars_to_load{3});
end
```

max_velocity.m | code_final.m | data_extract.m | new_file.m

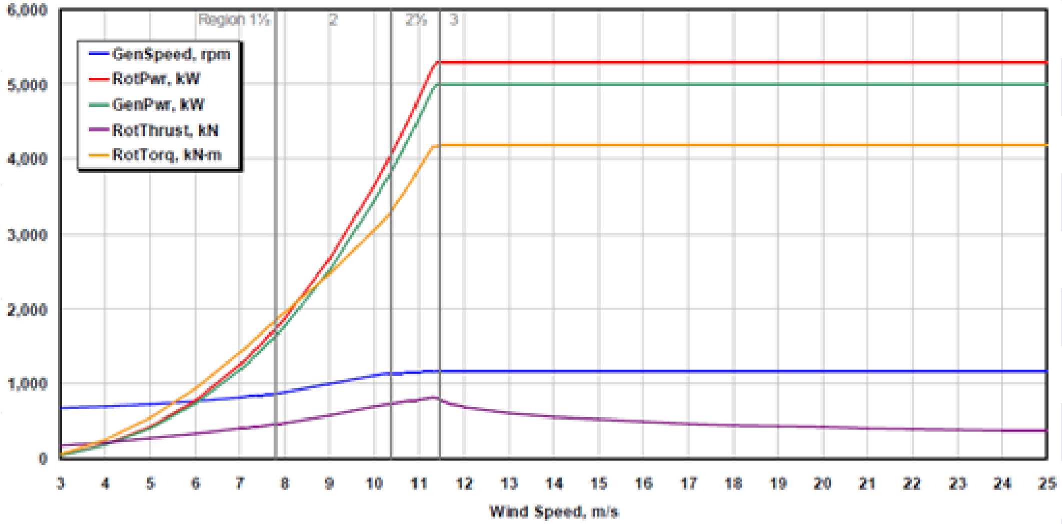
```
%z=zeros(12,457);
for q=1:457
    for n=1:12
        p=wind_velocity{1,q};
        p(isnan(p))=0;
        w(n,q)=max(p(n,:));


    end
end
for q=1:457
    for n=1:12
        rc=find(wind_velocity{1,q}(n,:)==w(n,q));
%         z(n,q)=wind_direction{1,q}(n,rc);
    end
end
final_mean = mean(w,2);
```

Height (m)	Average Windspeed (m/s)
40	12.8472
56.67	13.4042
73.4	13.9984
90.01	14.242
106.68	14.491
123.35	15.0871
140.02	15.7491
156.69	16.4324
173.36	17.2114
190.03	17.9142
206.67	18.3965
223.37	16.6033

Characteristics of 5MW turbine

- **Used NREL 5MW turbine as base turbine for analysis at Morro Bay.**
- **Semi-Submersible turbine was chosen given the depth of water at site (200m) and the advantages of the mounting such as cost of assembly and ease of installation**

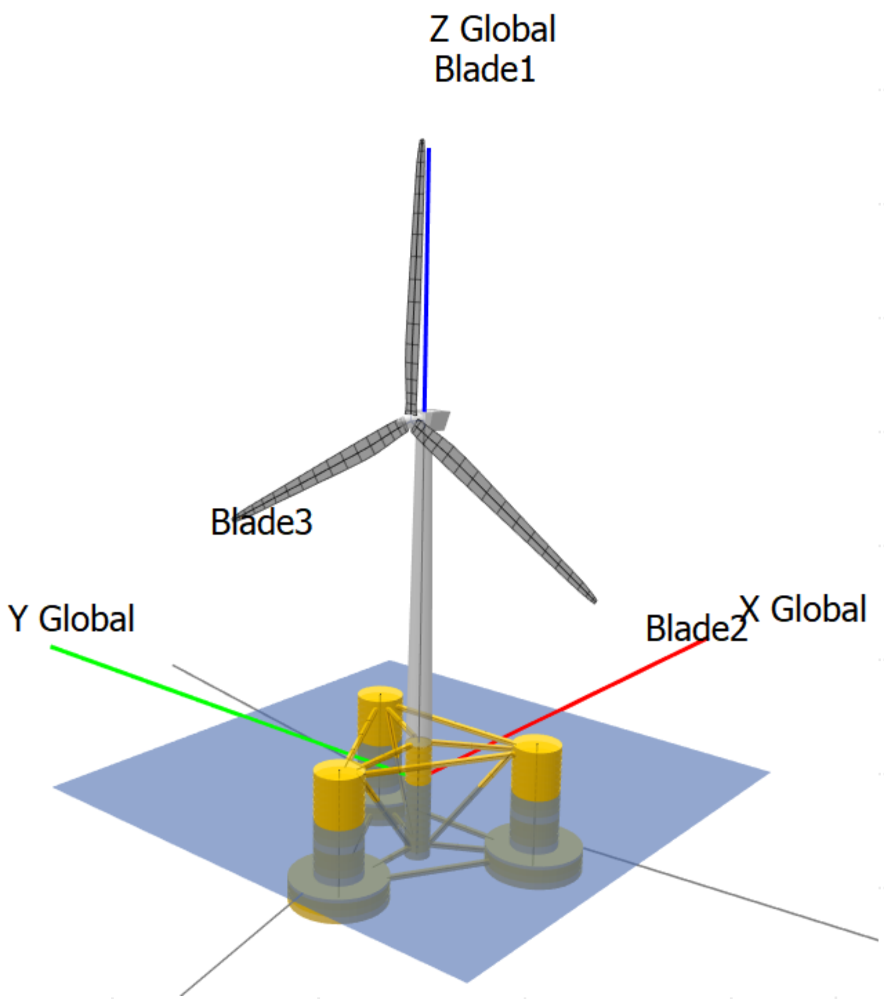


Node	RNodes(m)	AeroTwst(°)	DRNodes (m)	Chord(m)	Airfoil Table
1	2.8667	13.308	2.7333	3.542	Cylinder1.dat
2	5.6000	13.308	2.7333	3.854	Cylinder1.dat
3	8.3333	13.308	2.7333	4.167	Cylinder2.dat
4	11.7500	13.308	4.1000	4.557	DU40_A17.dat
5	15.8500	11.480	4.1000	4.652	DU35_A17.dat
6	19.9500	10.162	4.1000	4.458	DU35_A17.dat
7	24.0500	9.011	4.1000	4.249	DU30_A17.dat
8	28.1500	7.795	4.1000	4.007	DU25_A17.dat
9	32.2500	6.544	4.1000	3.748	DU25_A17.dat
10	36.3500	5.361	4.1000	3.502	DU21_A17.dat
11	40.4500	4.188	4.1000	3.256	DU21_A17.dat
12	44.5500	3.125	4.1000	3.010	NACA64_A17.dat
13	48.6500	2.319	4.1000	2.764	NACA64_A17.dat
14	52.7500	1.526	4.1000	2.518	NACA64_A17.dat
15	56.1667	0.863	2.7333	2.313	NACA64_A17.dat
16	58.9000	0.370	2.7333	2.086	NACA64_A17.dat
17	61.6333	0.106	2.7333	1.419	NACA64_A17.dat

Wind turbine used for analysis

Table 1-1. Gross Properties Chosen for the NREL 5-MW Baseline Wind Turbine

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

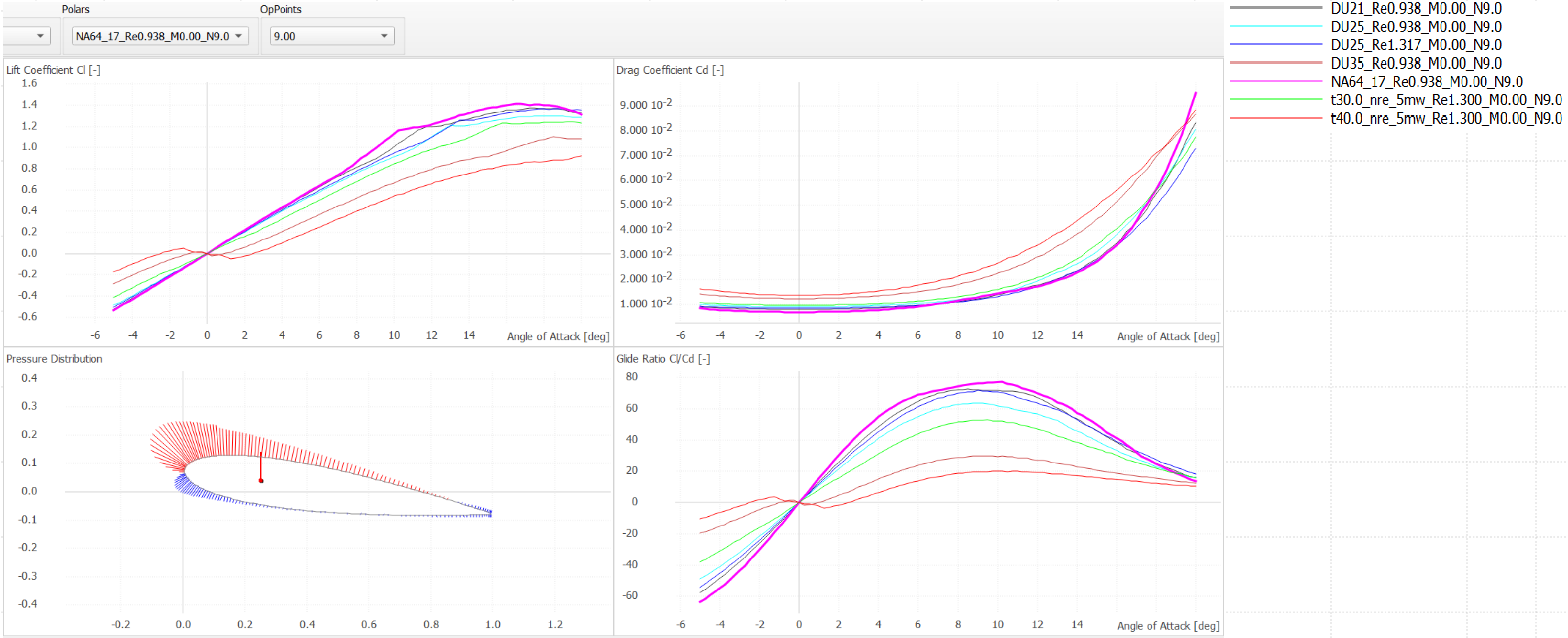


What is QBlade?

- **Qblade software is a highly advanced multi-physics code that covers the complete range of aspects required for the aero-servo-hydro-elastic design, prototyping, simulation, and certification of wind turbines. It uses BEM (Blade Element Momentum Theory) to run simulations on various wind turbines.**
- **Aerodynamic module to design blade and perform XFoil analysis by accounting for range of Angle of attack and Reynolds number.**
- **Three types of BEM modeling in QBlade:**

1. **Rotor BEM: Modelling for aerodynamic outputs (Power and thrust coefficient) of blade profile**
2. **Characteristic BEM: Modelling to predict power, thrust and torque output and using a given pitch range to optimise control characteristics**
3. **Turbine BEM: Modelling power and thrust output accounting for rated capacity, transmission type and losses.**

X-Foil analysis on airfoils of NREL 5MW OSW Semisubmersible

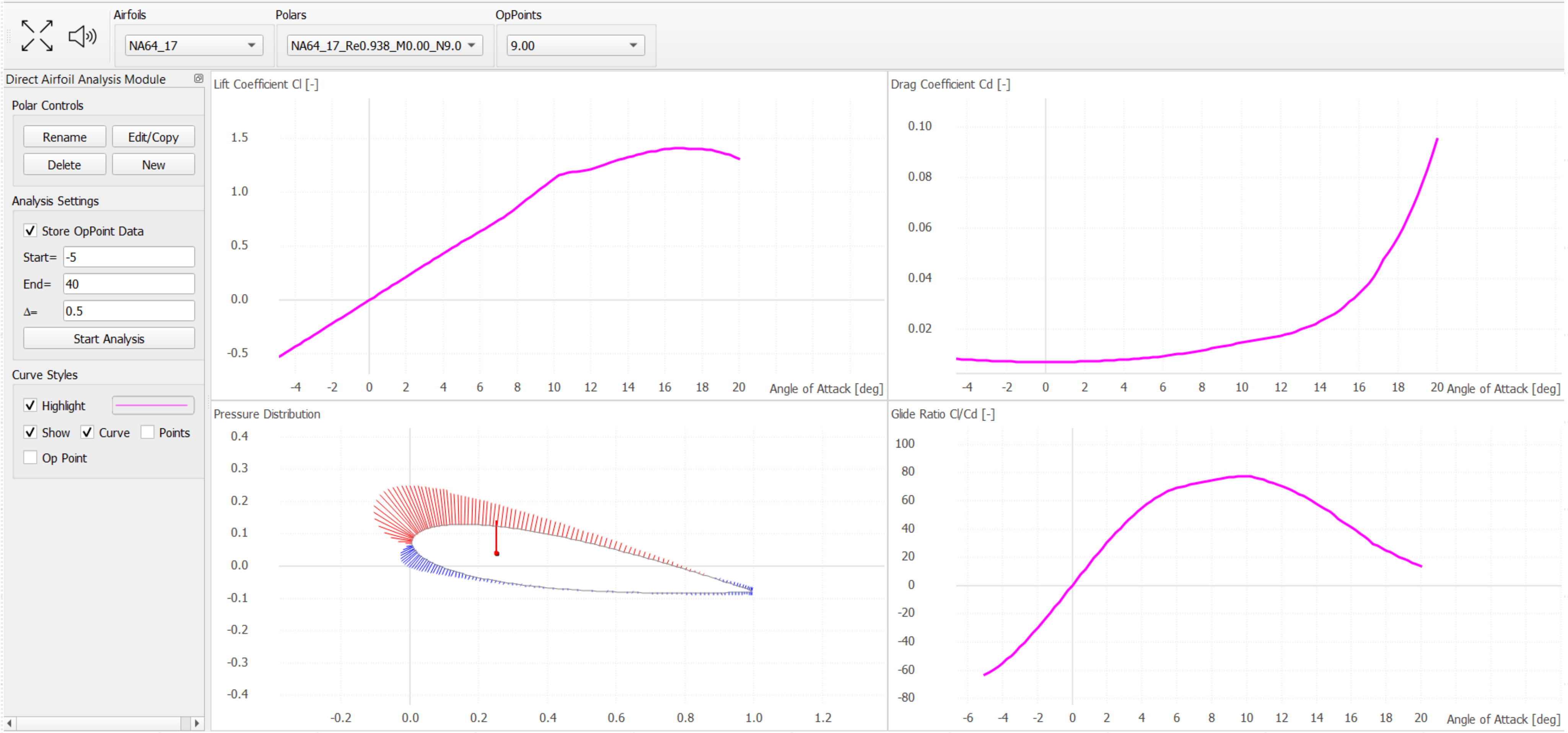


- Done using XFoil module in QBlade
  Analysis done on entire turbine blade collectively over angle of attacks ranging from –5 to 20
- Can be observed NA64 gives the best Cl v/s Cd values at an AoA of 9 and a desirable pressure distribution

Lift coefficients of all airfoils

	DU21_Re0.938_M0.00_N9.0	DU25_Re0.938_M0.00_N9.0	DU35_Re0.938_M0.00_N9.0	NA64_17_Re0.938_M0.00_N9.0	t30.0_nre_5mw_Re0.938_M0.00_N9.0	t40.0_nre_5mw_Re0.938_M0.00_N9.0
Angle of Attack	**Cl**	**Cl**	**Cl**	**Cl**	**Cl**	**Cl**
-5.000	-0.528	-0.491	-0.285	-0.537	-0.414	-0.153
-4.750	-0.502	-0.469	-0.265	-0.511	-0.392	-0.083
-4.500	-0.476	-0.446	-0.246	-0.485	-0.369	-0.051
-4.000	-0.424	-0.422	-0.225	-0.458	-0.347	-0.021
-3.750	-0.398	-0.399	-0.205	-0.432	-0.324	0.007
-3.500	-0.372	-0.350	-0.187	-0.405	-0.302	0.030
-3.250	-0.346	-0.326	-0.167	-0.379	-0.280	0.046
-3.000	-0.319	-0.301	-0.147	-0.352	-0.257	0.029
-2.750	-0.293	-0.276	-0.130	-0.325	-0.237	0.011
-2.500	-0.267	-0.251	-0.110	-0.298	-0.216	0.000
-2.250	-0.240	-0.227	-0.092	-0.271	-0.195	-0.011
-2.000	-0.213	-0.201	-0.076	-0.244	-0.176	-0.028
-1.750	-0.187	-0.177	-0.058	-0.217	-0.157	-0.045
-1.500	-0.161	-0.152	-0.042	-0.190	-0.142	-0.030
-1.250	-0.134	-0.126	-0.028	-0.163	-0.123	-0.007
-1.000	-0.107	-0.101	-0.014	-0.136	-0.105	0.021
-0.750	-0.080	-0.076	-0.001	-0.109	-0.083	0.051
-0.500	-0.053	-0.051	0.009	-0.082	-0.042	0.083
-0.250	-0.027	-0.026	0.015	-0.054	-0.021	0.153
0.000	0.000	0.000	0.020	-0.027	0.000	0.190
0.250	0.027	0.026	0.000	0.000	0.021	0.224
0.500	0.053	0.050	-0.021	0.027	0.042	0.263
0.750	0.080	0.076	-0.015	0.054	0.083	0.296
1.000	0.107	0.101	-0.009	0.082	0.105	0.335
1.250	0.134	0.126	0.001	0.109	0.123	0.405

X-foil analysis of NACA64_17

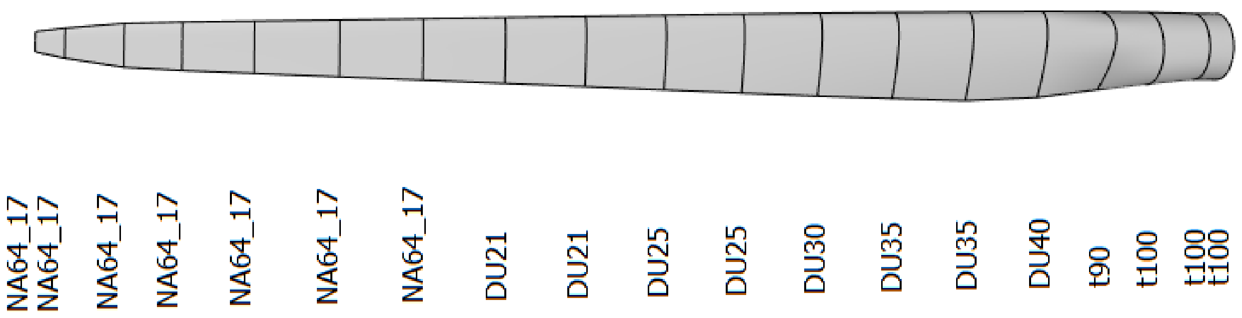


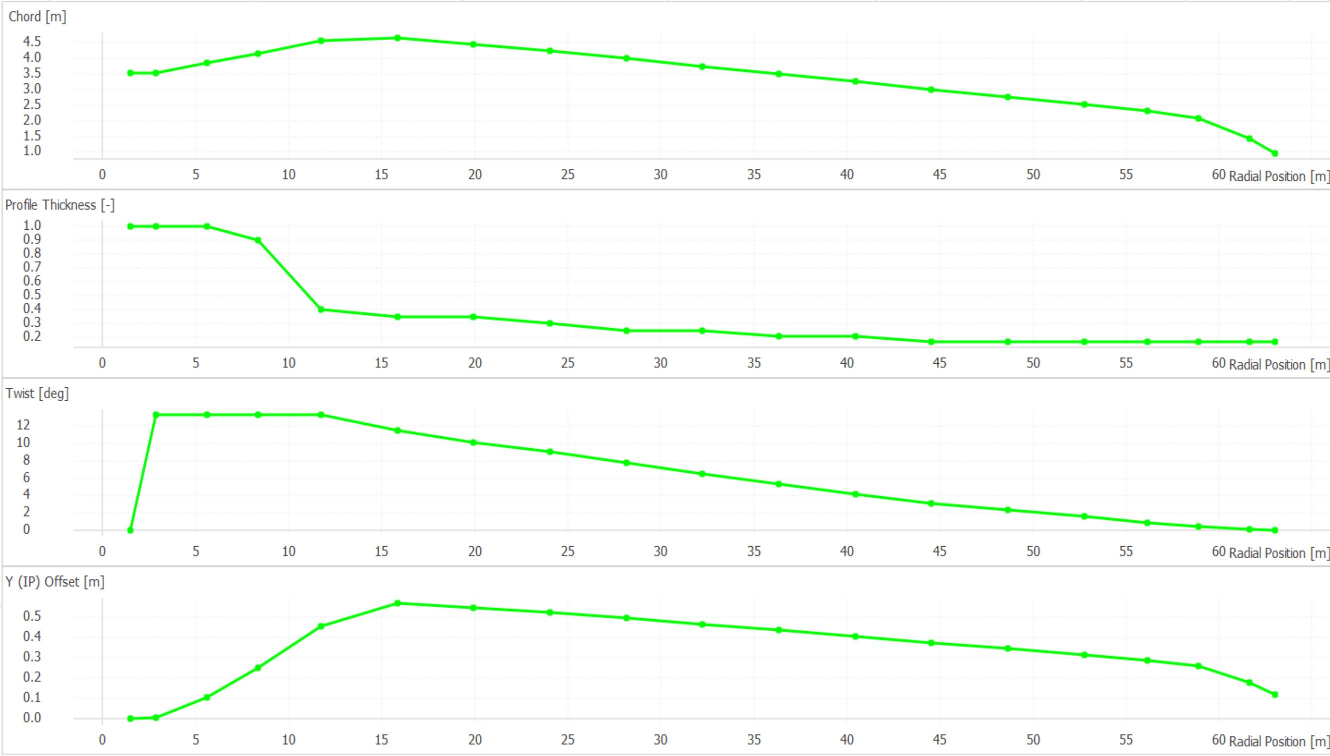
- **Cl is seen to linearly increasing from –5 to 16**
- **At 14º stall development is seen and stall regime is seen to fully develop at 16º**

Airfoil sections

- **Used NA64, DU25 and DU21 airfoils for most part of primary and tip section due to good lift characteristics**

- **Given are the variations of Chord, Twist and Thickness with Radial Variation i.e., distance from hub centre**

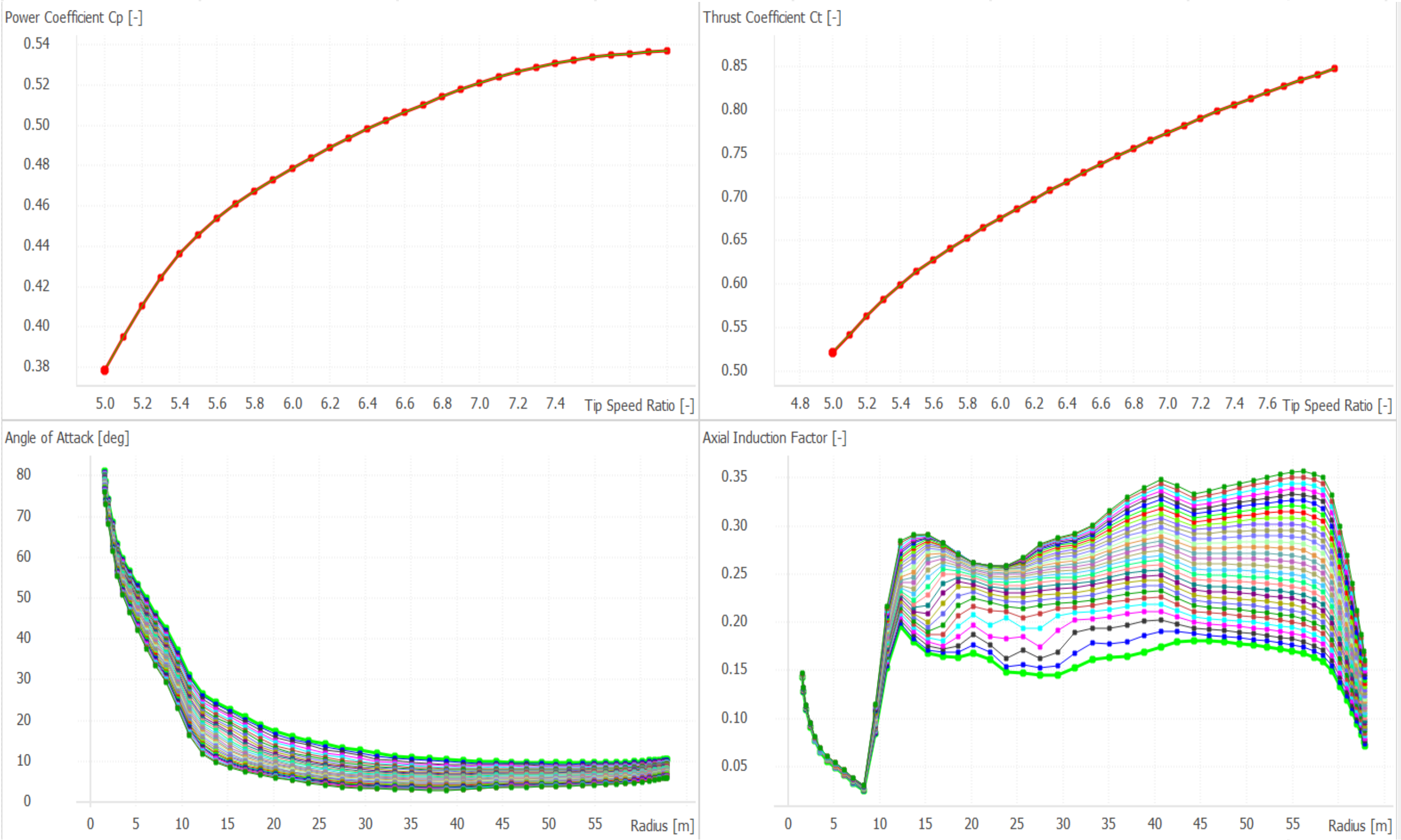




Rotor BEM

- Rotor characteristics of blade showing variation of power and thrust coefficients with respect to tip speed ratio ranging from 5 to 8.

- Variation of angle of attack for all airfoils along the radius

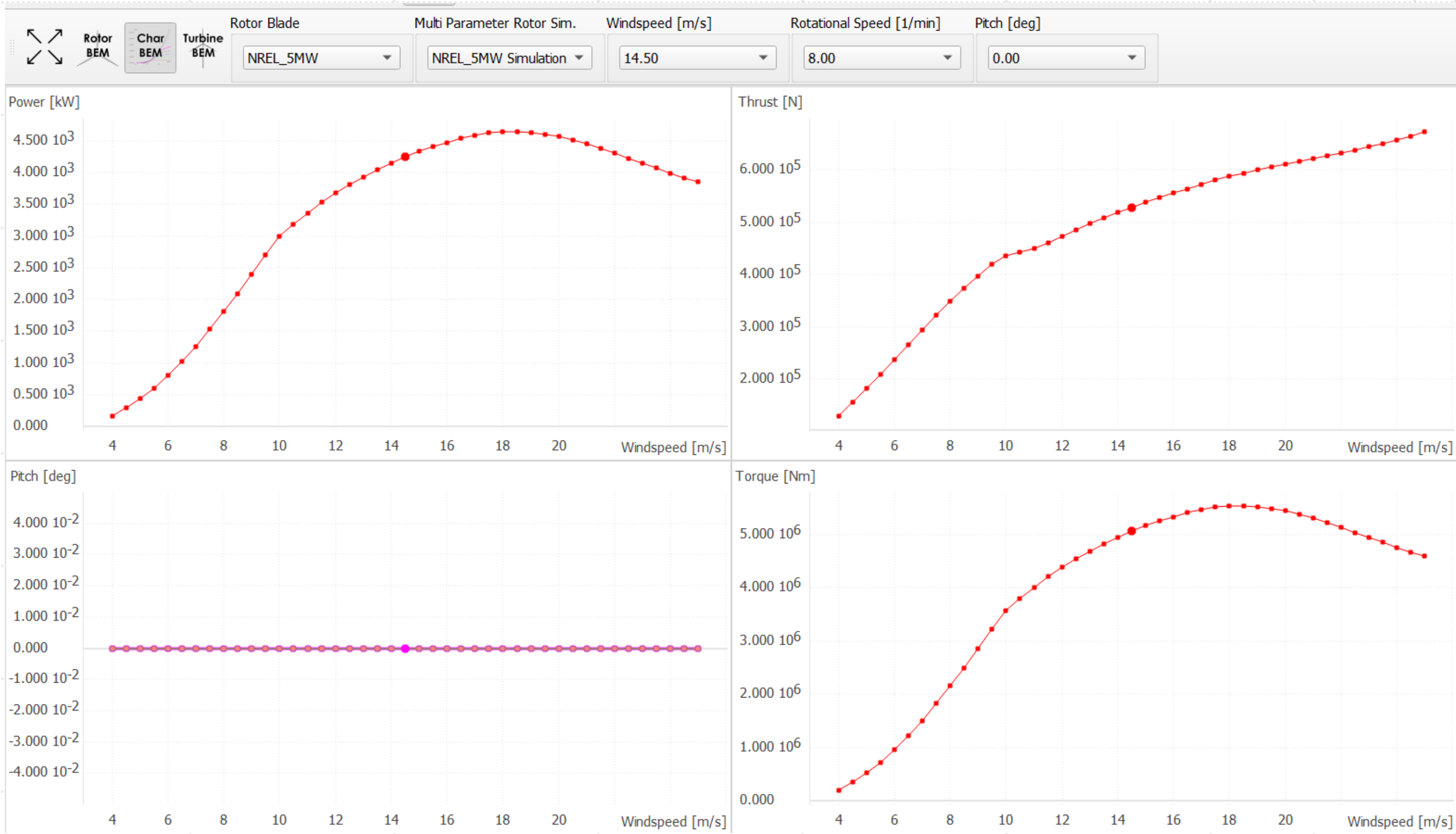


Characteristic BEM

- It is observed at 8RPM, power curve approaches rated power at about 4.5MW at the mean velocity of 14.24 m/s.

- The thrust is seen to be 500kN at 14m/s

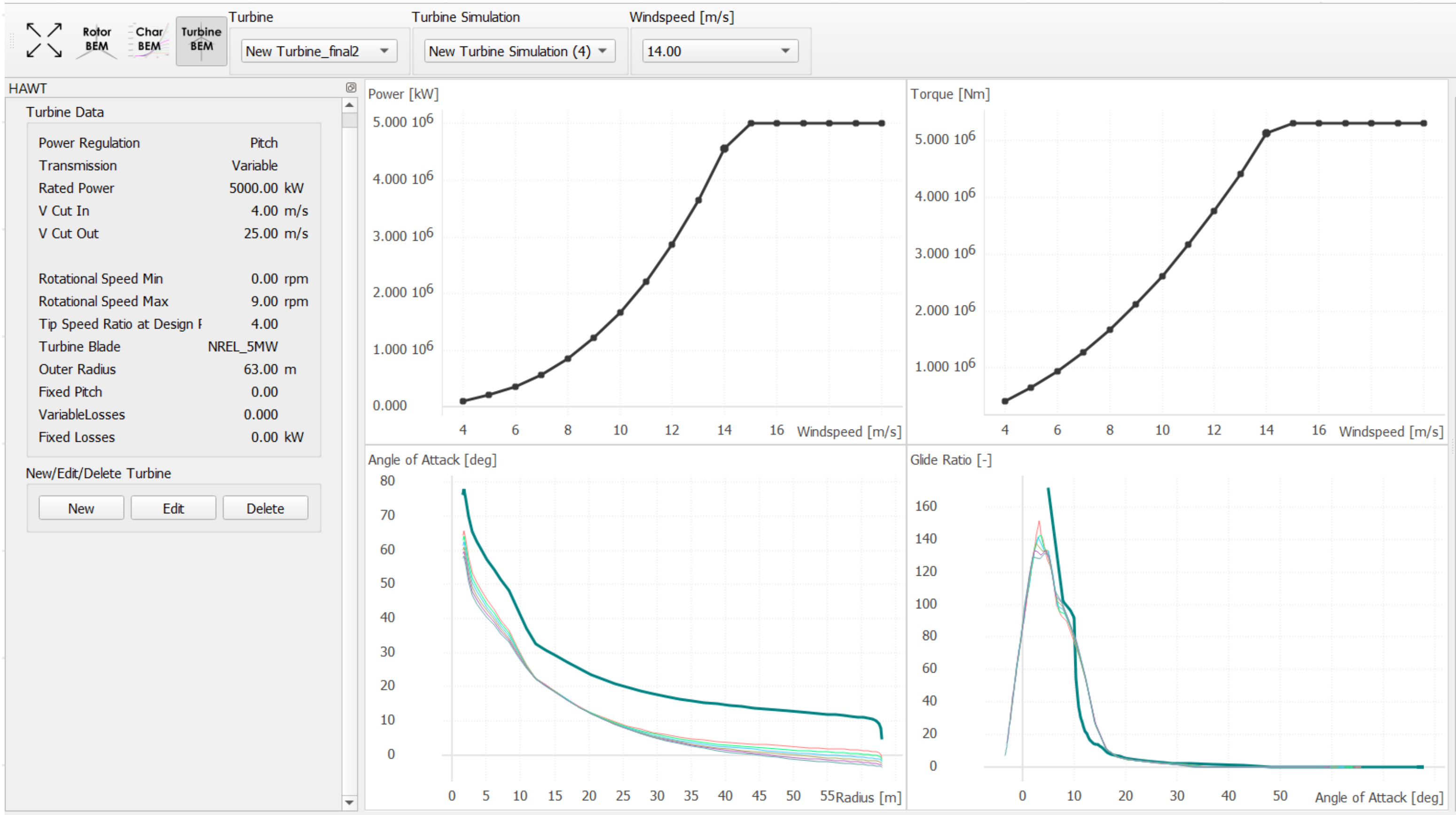
- Torque is 500kNm at 14m/s



Turbine BEM

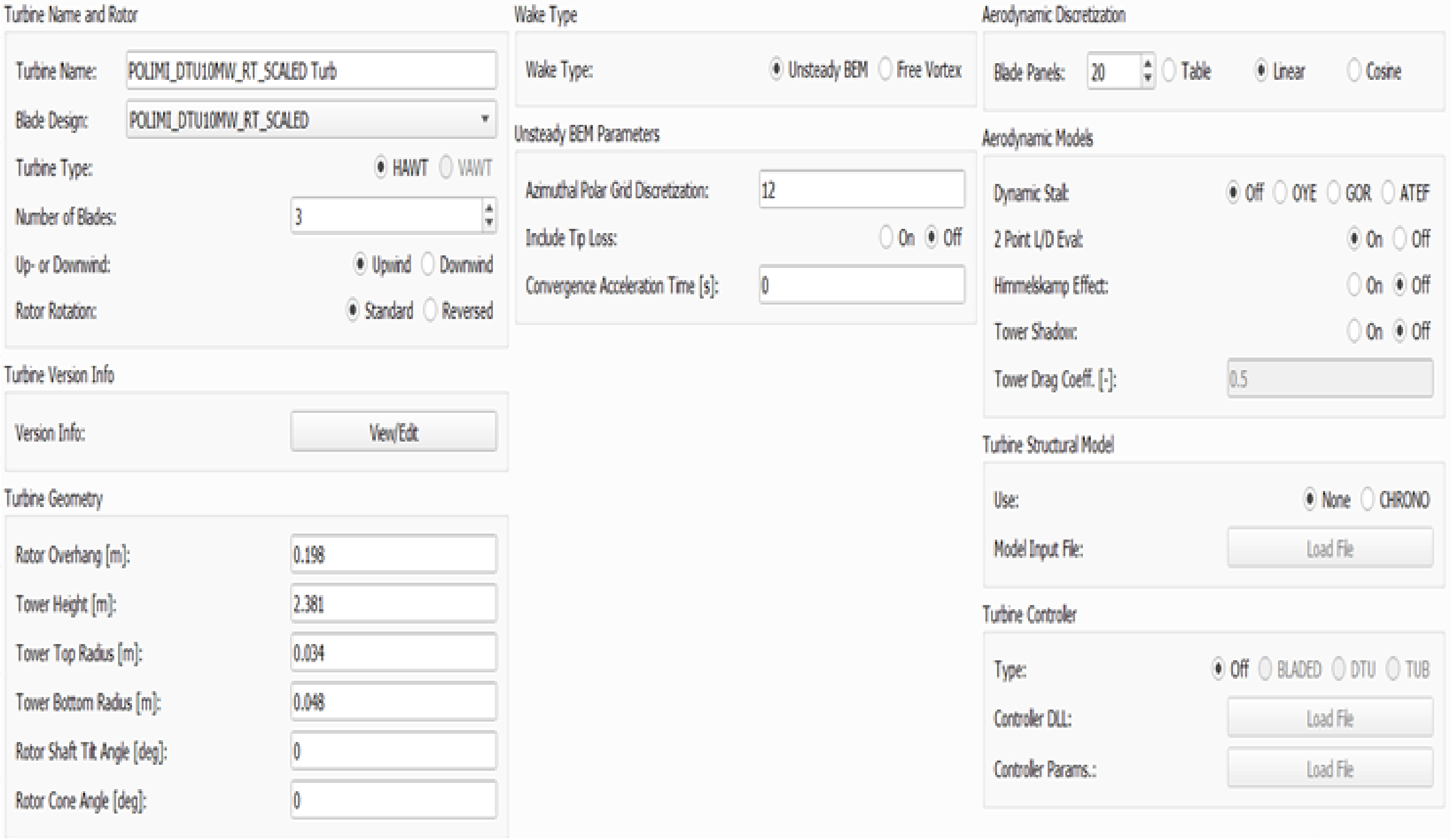
- **Using rated power at 5MW, velocity range between 4 – 25 m/s power and torque curve v/s windspeed was obtained**

- **Angle of attack v/s radius and Cl/Cd (Glide ratio) v/s AoA can be observed**



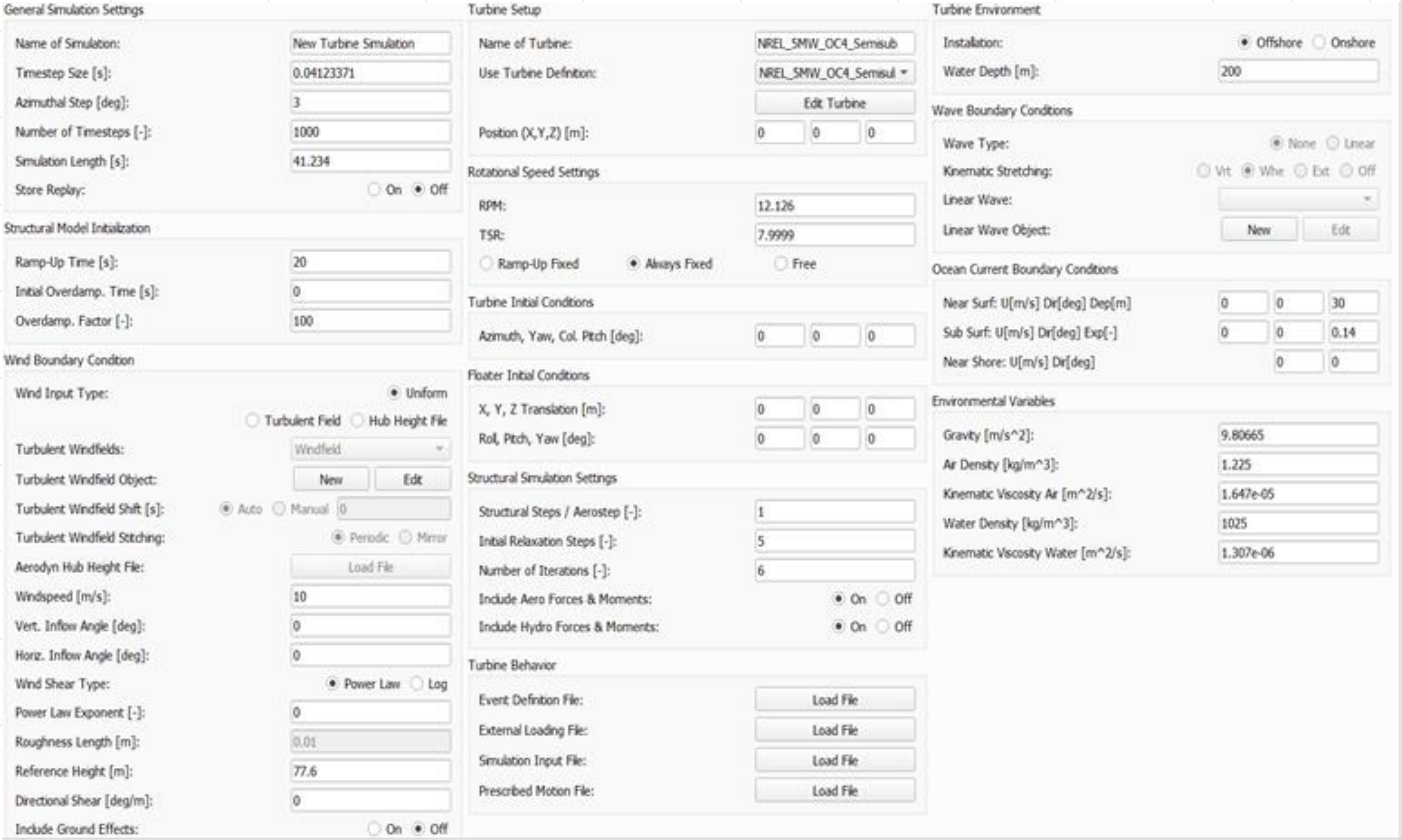
Turbine Definition Module

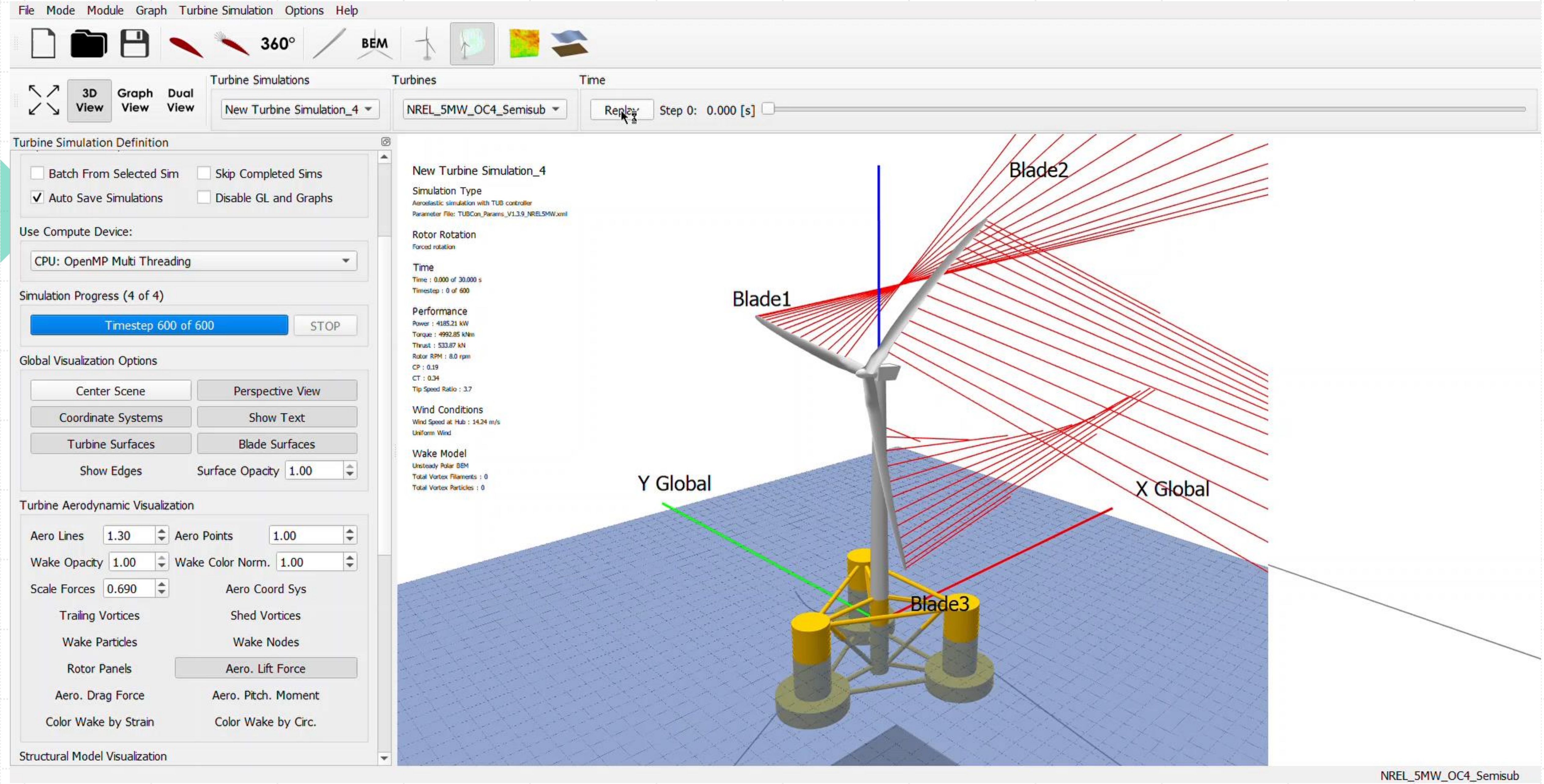
- **Used to define turbine simulation taking into account mean velocity, max RPM and Tip speed ratio**
- **Can account for Himmelskamp effect and tower shadow if needed**
- **Possible to include definitions for Linear or any other types of wave definitions if required**



Turbine Simulation Module

- Input is velocity of 14.24m/s
- Max RPM is set to 12.126
- TSR is automatically calculated
- Water depth is set to 200m.





File
Mode
Module
Graph
Turbine Simulation
Options
Help
360°
BEM
3D View
Graph View
Dual View
Turbine Simulations
New Turbine Simulation_4
Turbines
NREL_5MW_OC4_Semisub
Time
Replay
Step 0: 0.000 [s]
Turbine Simulation Definition
Batch From Selected Sim
Skip Completed Sims
Auto Save Simulations
Disable GL and Graphs
Use Compute Device:
CPU: OpenMP Multi Threading
Simulation Progress (4 of 4)
Timestep 600 of 600
STOP
Global Visualization Options
Center Scene
Perspective View
Coordinate Systems
Show Text
Turbine Surfaces
Blade Surfaces
Show Edges
Surface Opacity 1.00
Turbine Aerodynamic Visualization
Aero Lines 1.30
Aero Points 1.00
Wake Opacity 1.00
Wake Color Norm. 1.00
Scale Forces 0.690
Aero Coord Sys
Trailing Vortices
Shed Vortices
Wake Particles
Wake Nodes
Rotor Panels
Aero. Lift Force
Aero. Drag Force
Aero. Pitch. Moment
Color Wake by Strain
Color Wake by Circ.
Structural Model Visualization
New Turbine Simulation_4
Simulation Type
Aeroelastic simulation with TUB controller
Parameter File: TUBCon_Params_V1.3.9_NREL5MW.xml
Rotor Rotation
Forced rotation
Time
Time : 0.000 of 30.000 s
Timestep : 0 of 600
Performance
Power : 4185.21 kW
Torque : 4992.85 kNm
Thrust : 533.87 kN
Rotor RPM : 8.0 rpm
CP : 0.19
CT : 0.34
Tip Speed Ratio : 3.7
Wind Conditions
Wind Speed at Hub : 14.24 m/s
Uniform Wind
Wake Model
Unsteady Polar BEM
Total Vortex Filaments : 0
Total Vortex Particles : 0
Blade2
Blade1
Blade3
Y Global
X Global
NREL_5MW_OC4_Semisub

Windspeed [m/s]	Power [kW]
4.00	-136.06
4.50	-7.00
5.00	154.59
5.50	348.71
6.00	576.78
6.50	839.92
7.00	1138.86
7.50	1473.60
8.00	1845.50
8.50	2256.00
9.00	2704.39
9.50	3190.22
10.00	3714.16
10.50	4272.99
11.00	4863.30
11.50	5479.71
12.00	6095.11
12.50	6734.49
13.00	7400.94
13.50	8086.69
14.00	8784.43
14.50	9470.22
15.00	10088.31
15.50	10553.04
16.00	10918.54
16.50	11324.08
17.00	11727.90

Windspeed [m/s]	Thrust [N]
4.00	147841.53
4.50	182691.28
5.00	219135.41
5.50	256220.08
6.00	294101.09
6.50	332710.41
7.00	372072.78
7.50	412035.50
8.00	452622.53
8.50	493726.41
9.00	535415.13
9.50	577434.63
10.00	619840.19
10.50	662228.31
11.00	704003.69
11.50	745231.63
12.00	784549.56
12.50	823096.25
13.00	859633.44
13.50	894535.38
14.00	927432.81
14.50	957429.38
15.00	981291.56
15.50	993656.94
16.00	999004.88

Windspeed [m/s]	Torque [Nm]
4.00	-108270.06
4.50	-5567.43
5.00	123016.27
5.50	277491.75
6.00	458985.31
6.50	668385.19
7.00	906272.50
7.50	1172657.00
8.00	1468600.00
8.50	1795265.50
9.00	2152082.80
9.50	2538693.00
10.00	2955638.00
10.50	3400338.80
11.00	3870090.30
11.50	4360611.50
12.00	4850333.00
12.50	5359134.50
13.00	5889480.50
13.50	6435184.00
14.00	6990424.50
14.50	7536162.00
15.00	8028019.00
15.50	8397843.00
16.00	8688700.00

Conclusions

- **Blade modelling using mean velocity of 14.24m/s retrieved from Morro Bay data done on QBlade. NA64_17, DU 25 and DU 21 profiles found to have the most optimal lift and pressure distributions.**
- **Stall from graphs is observed at AoA of 16^{o} at Cl 1.4 and Cd 0.03 for NA64_17**
- **Power curve shows it maxes out at 18m/s and 8RPM given a rated capacity of 5MW.**
- **Torque value is 699kNm at 14m/s and shows maximum value of 987kNM at 18m/s after which drag characteristics become predominant.**
- **Thrust value for this particular turbine was found to be 981 kN at 14m/s and 1064kN at cut out velocity of 25m/s.**

THANK YOU!