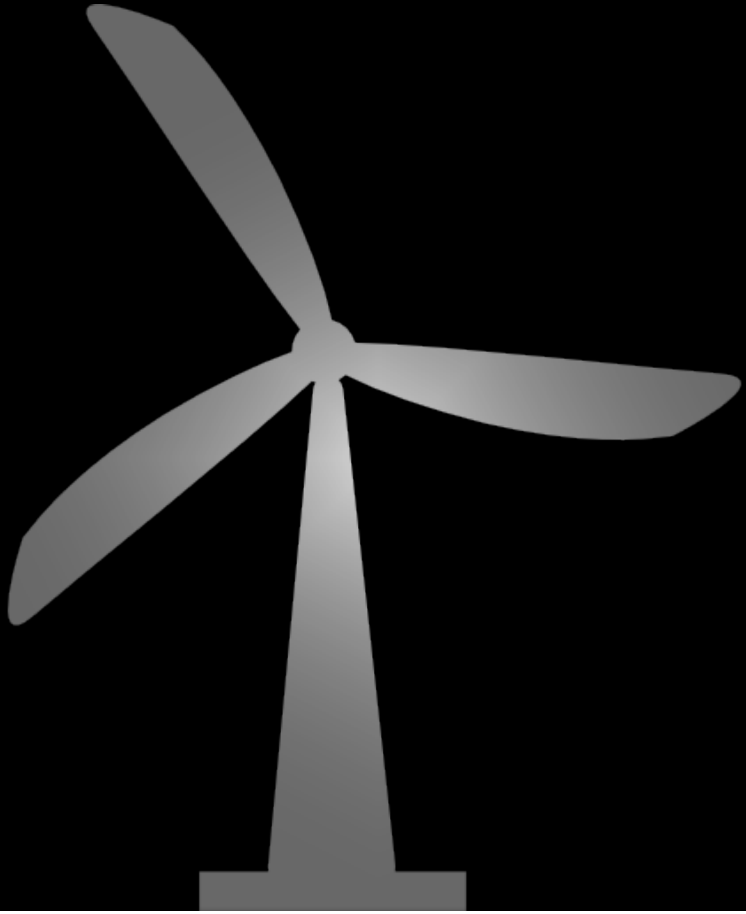
PROVA FINALE DEL CORSO MECCHINE
PROF. GIACOMO BRUNO AZZURO PERSICO

DESIGN OF WIND TURBINE



GROUP 2:

CAI ZHONGTIAN 875870
CHEN DELI 875836
JI XIONG 876899
RONG YUXUAN 876754
SHI ZHENYU 875969

WORKING CONDITIONS

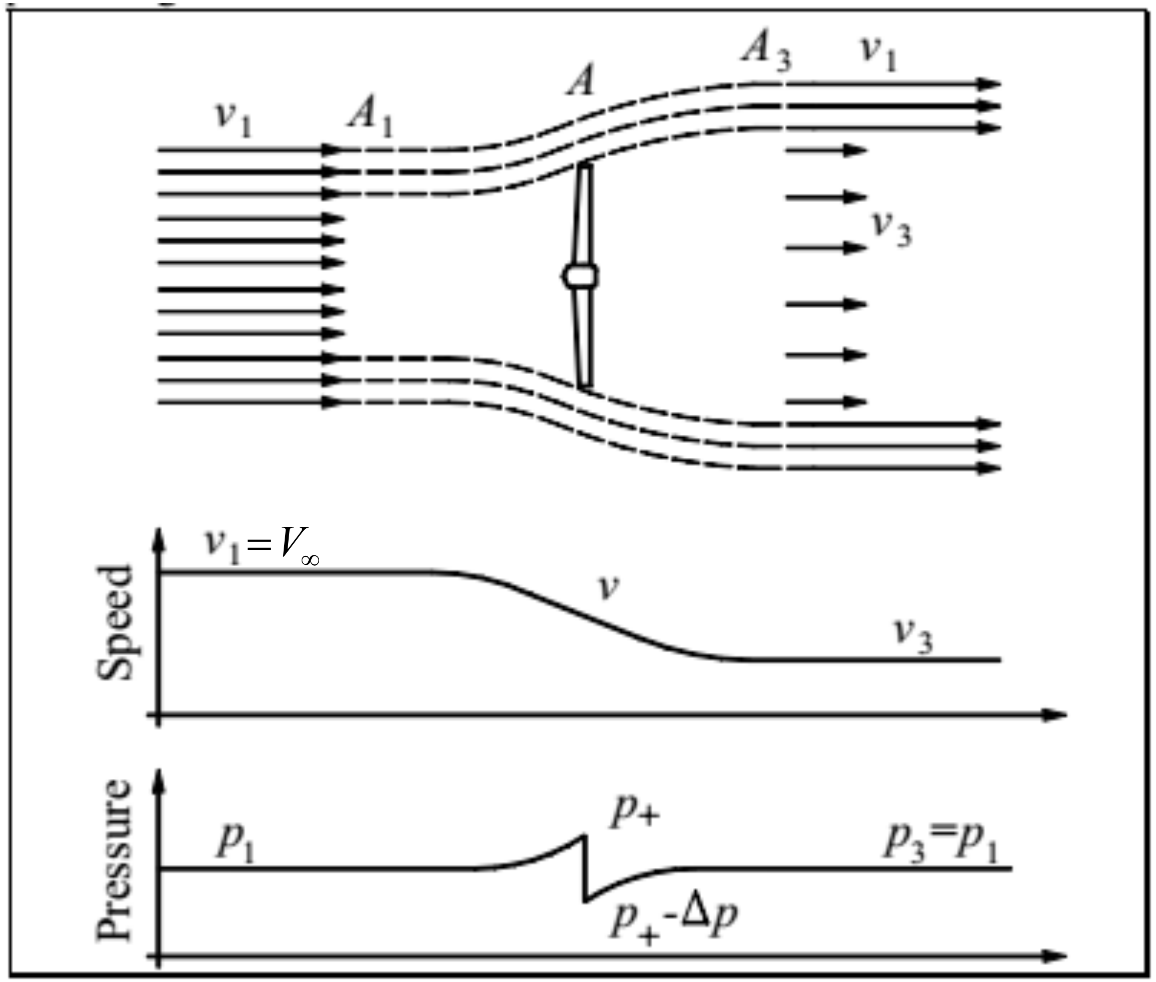
- Wind velocity: V_∞ =10m/s
- Temperature: T=15℃=288K
- Altitude: Z_{sito} =900m
- Nominal Mechanical Power: $W = 40(1 + i) = 120\ kW$ *(i=2)*

REQUEST

- Calculation of the external diameter $\boldsymbol{D}$ and the blade height h.
- Calculation of the rotating speed $\boldsymbol{n}$.
- Velocity Triangle at the rotor's entrance in correspondence of at least three sections along the blade height (primary, hub, tip), after having chosen the profile (or profiles) with the use of an appropriate database.
- Evolution of the chord $\boldsymbol{C}$ and the crank angle $\boldsymbol{\gamma}$ along the blade height.
- Coefficient of power $\boldsymbol{C_p}$ as an index of machine efficiency.
- Velocity triangle along the blade height and the coefficient of power $\boldsymbol{C_p}$ in out-of-air condition in which the machine previously designed for wind speed of : $V_\infty = 8 m/s$ and $V_\infty = 12 m/s$

CALCULATION

External diameter D & blade height h



- In order to determine these two factors, we need to know the speeds at three locations: V_∞ V_D V_3
- And in order to determine these speeds, the axial interference factor "a" must be known.
- According to the HAWT-NOTE, a is also called the induction factor, and is defined by the following formula:
- $a=(V_\infty-V)/V_\infty$ =1/3

CALCULATION

External diameter D & blade height h

- $a = \frac{1}{3} \rightarrow$
- $V_D = (1-a)V_\infty = \frac{2}{3}V_\infty = 6.67\ m/s$
- $V_3 = (1-2a)V_\infty = \frac{1}{3}V_\infty = 3.33\ m/s$
- Since our work station is built at an altitude of 900 meters, we have to consider the gradient of pressure.
- $Z_{sito} = 900\ m \qquad \frac{\partial P}{\partial z} = -10^{-4}\,\frac{bar}{m} \qquad \rightarrow$
- $\Delta P_{atm} = -10^{-4} * 900 = -0.09$ bar
- $P_{atm} = 1 + \Delta P_{atm} = 0.91$ bar

CALCULATION

External diameter D & blade height h

- Using the pressure on site, we have:

$$PV_{\text{volume}} = RT \qquad \frac{P}{\rho} = RT \qquad R = 287 J / kg \cdot K$$

$$T = 273.15 + 15 = 288.15 K \Rightarrow$$

$$\rho = \frac{P}{RT} = \frac{0.91 \times 10^5 \dfrac{N}{m^2}}{287 \times 288.15 \dfrac{J}{kg}} = 1.1 kg / m^3$$

CALCULATION

External diameter D & blade height h

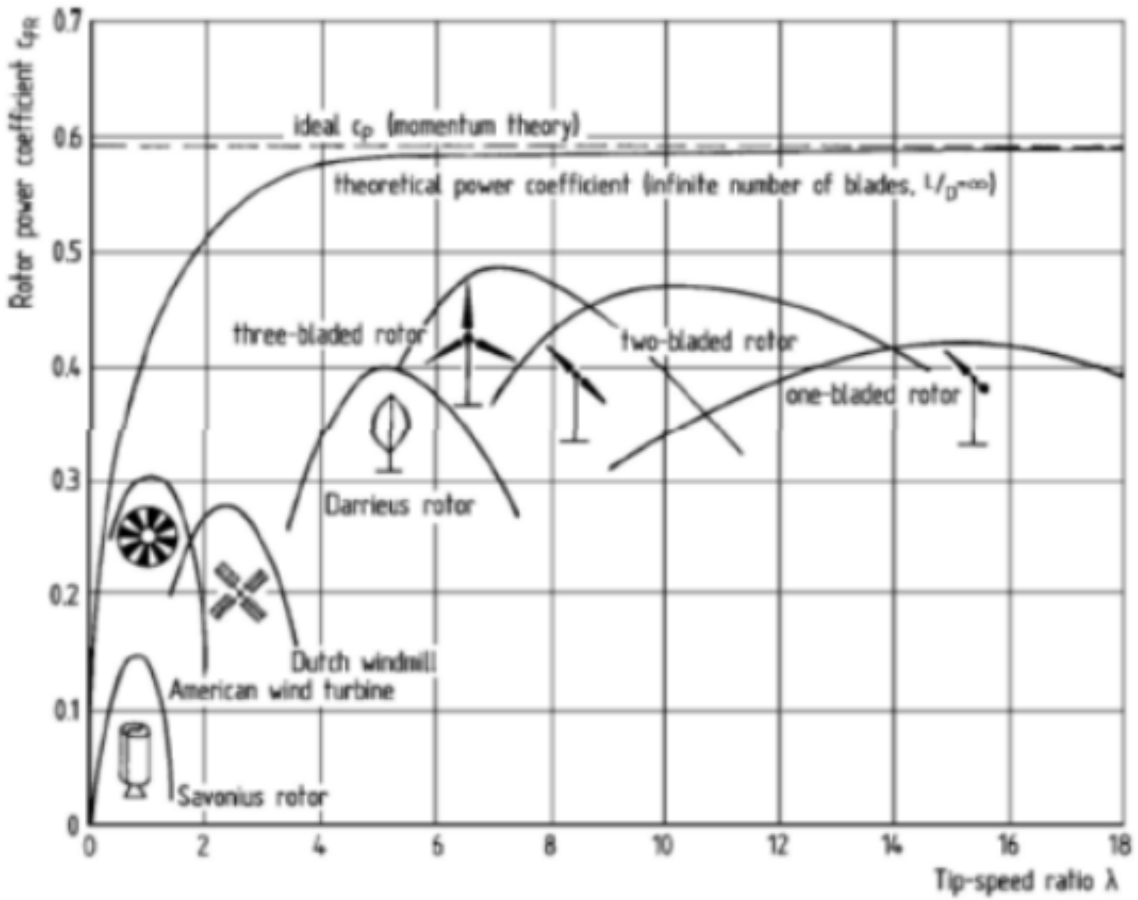
- The coefficient of power production C_p is defined as:
- $C_p = \frac{P_e}{P_d} = 4a(1-a)^2$
- The theoretical maximum value of C_p is:

$$C_p = \frac{16}{27} \approx 0.593$$

- However, we still have to determine the maximum value of C_p in reality.

CALCULATION

External diameter D & blade height h



- We choose to design the three-blade wind turbine.

- According to the diagram of tip ratio and C_p, we can easily get three-blade wind turbine's optimal coefficient:
  $C_p \approx 0.48$

CALCULATION

External diameter D & blade height h

- Using the continuity equation the mass flow $\dot{m} = \rho V_\infty S_D$

  where $\rho = 1.1\ kg/m^3$

  $$S_D = \frac{\pi D^2}{4}$$

- Thus we can calculate D from the power extracted by the actuator which equals coefficient C_p times the disponibile power P_d
- $W = C_p * P_d = C_p * \frac{1}{2} m {V_\infty}^2 = C_p * \frac{1}{2} \rho S_D {V_\infty}^3 = C_p * \frac{1}{2} \rho \frac{\pi D^2}{4} {V_\infty}^3$

  $= 120000\ W$

→ $D \approx 24.1\ m$

CALCULATION

External diameter D & blade height h

- Balancing the economic and structural needs, the ratio between the external and internal radius has to be chosen in the range $0.1 \le \frac{r_i}{r_e} \le 0.2$

- We choose

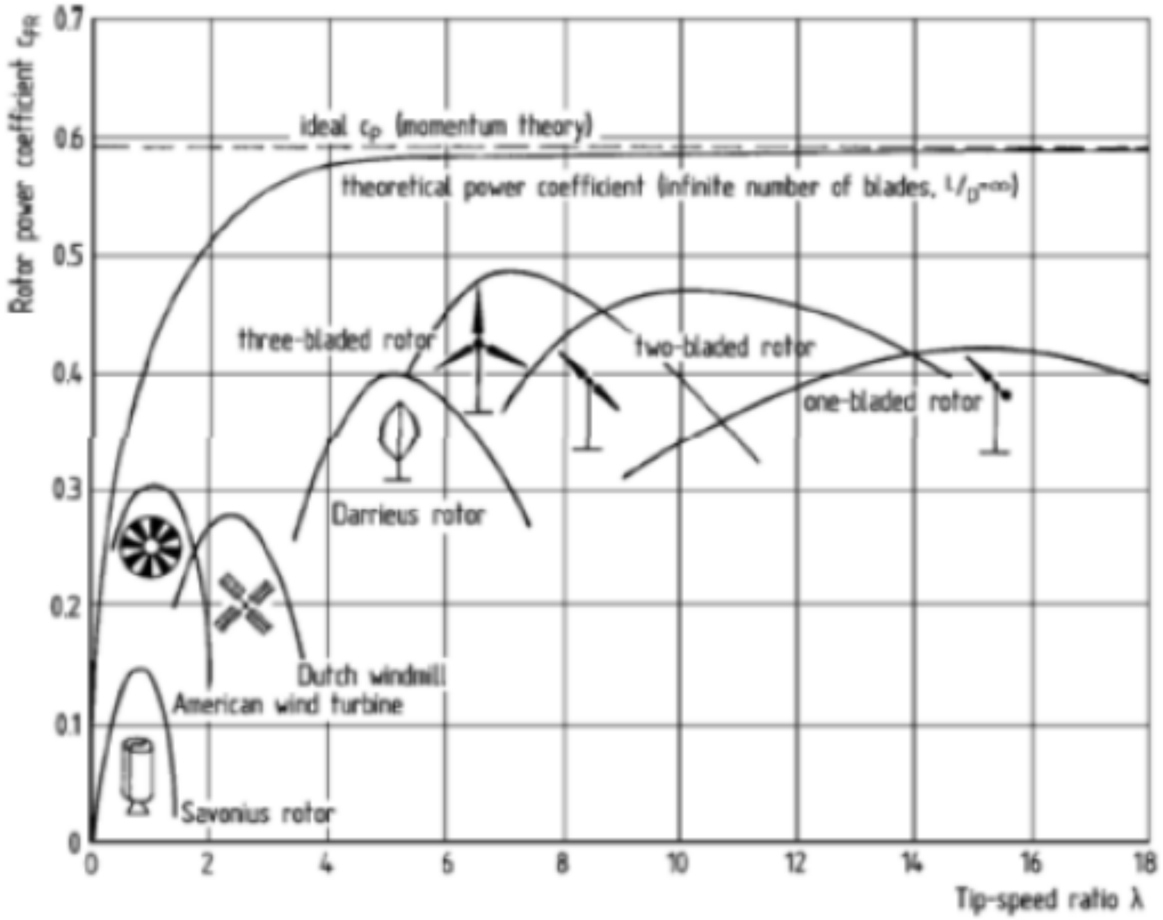
$$\frac{r_i}{r_e} = 0.2$$

$$\rightarrow h = r_e - r_i = 0.8 r_e = 0.8 * \frac{D}{2} = 9.64 m$$

- Therefore, we get the blade height h.

CALCULATION

Rotation speed n



- We can also get the tip ratio from the graph
  $\lambda \approx 7.2$

- Since $\lambda = \frac{V_{tip}}{V_D} = \frac{\omega * \frac{D}{2}}{\frac{2}{3} V_\infty}$

  $\rightarrow \omega = 3.98\, rad/s$

  $n = 38.04\, rpm$

Selection of the blade-section profile

- We choose to change the profile along the height.

- Three main adimensional blade section is selected:

Hub Profile	20% Radius
Primary Profile	75% Radius
Tip Profile	95% Radius

- The database of the blade-section profile refers to NREL.

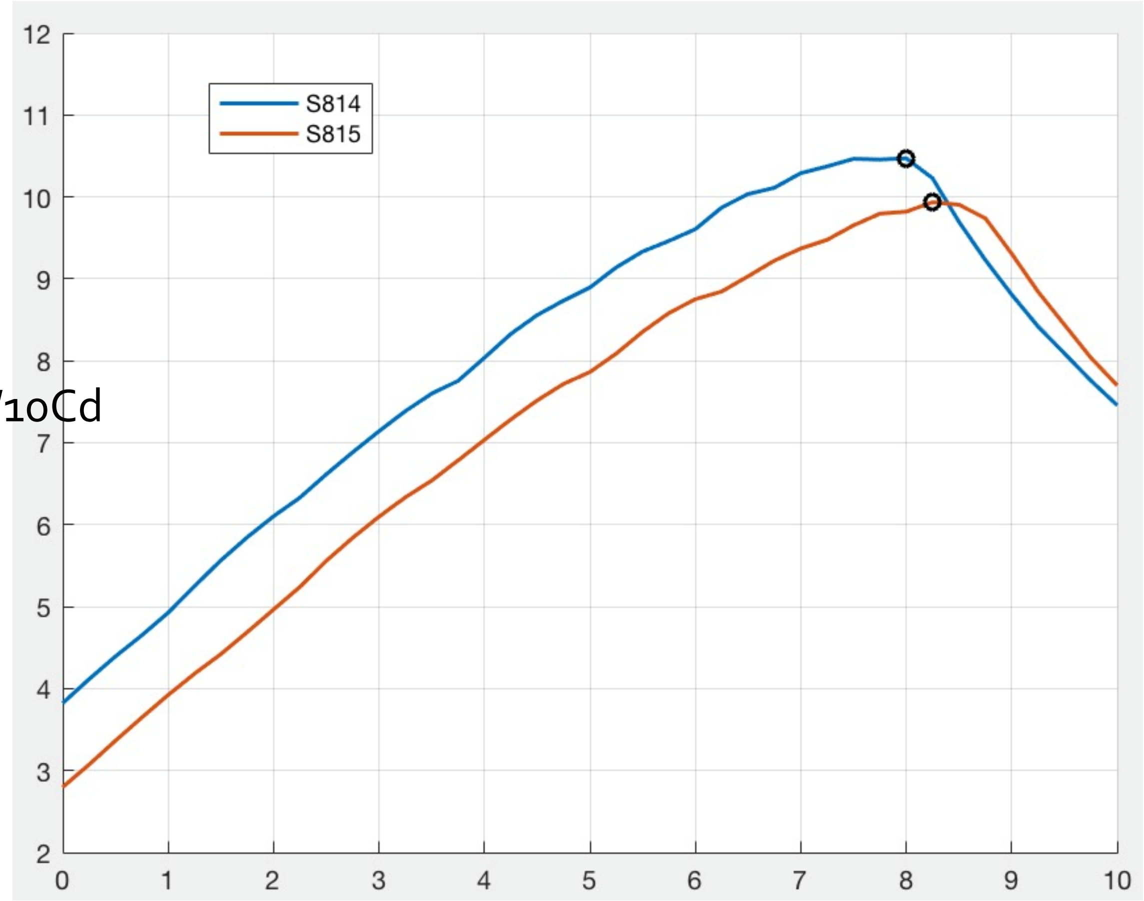
Selection of the blade-section profile

NREL's S-Series Airfoil Families

Rotor Diameter	Category	Root	Primary	Tip
1–3 m	Thick	S835	S833	S834
3–10 m	Thick	S823	-	S822
10–20 m	Thin	~~S804~~	~~S801~~	~~S802~~
	Thin	~~S804~~	~~S801~~	~~S803~~
	Thin	S807	~~S805~~	~~S806~~
	Thin	S807	S805A	S806A
	Thin	S808	S805A	S806A
	Thick	S821	S819	S820
20–30 m	Thick	S811	S809	S810
	Thick	S814	S812	S813
	Thick	S815	S812	S813
20–40 m	-	S814	S825	S826
	-	S815	S825	S826
	-	-	-	S829
30–50 m	Thick	S818	S816	S817
40–50 m	Thick	S818	S830	S831
	Thick	S818	S830	S832
	Thick	S818	S827	S828

- Based on the rotor diameter we just calculated (D=24.1 m), we choose the profile shape according to the NREL’s airfoil families:
- S814 for Hub
- S825 for Primary
- S826 for Tip

Selection of the blade-section profile



Cl/10Cd

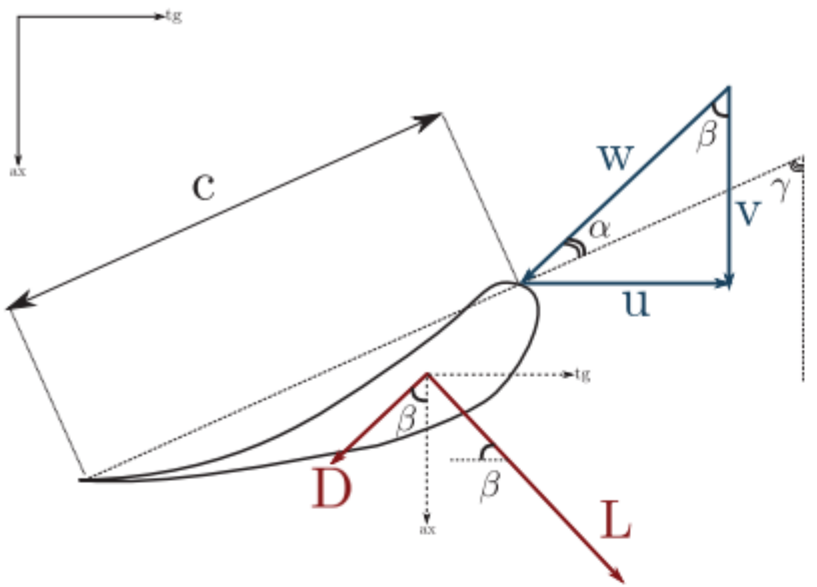
α

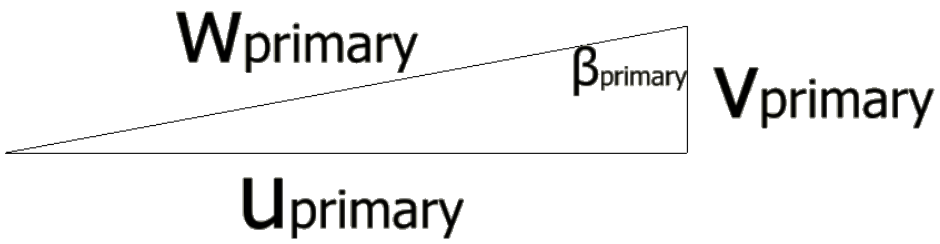
- The reason we choose S814 for Hub instead of S815 for Hub:

  Cl/10*Cd (S814)> Cl/10*Cd (S815)

VELOCITY TRIANGLE

S825-Primary (75% Radius)

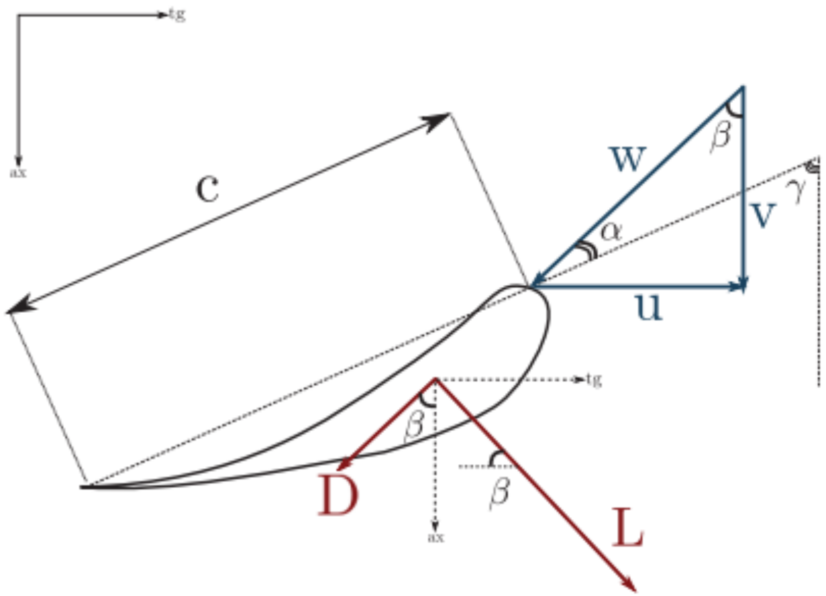


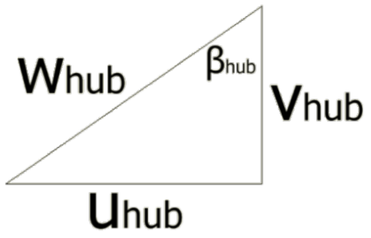


- $R_{\text{primary}} = \frac{D}{2} * 75\% = 9.0375\, m$
- $u_{\text{primary}} = \omega * R_{\text{primary}} = 35.97\ {}^{m}/_{s}$
- $v_{\text{primary}} = v_D = 6.67\ {}^{m}/_{s}$
- $w_{\text{primary}} = \sqrt{u_{\text{primary}}{}^2 + v_{\text{primary}}{}^2}$
  $= 36.58\ {}^{m}/_{s}$
- $\beta_{\text{primary}} = \arctan\left(\frac{u_{\text{primary}}}{v_{\text{primary}}}\right) = 79.5°$

VELOCITY TRIANGLE

S814-Hub (20% Radius)

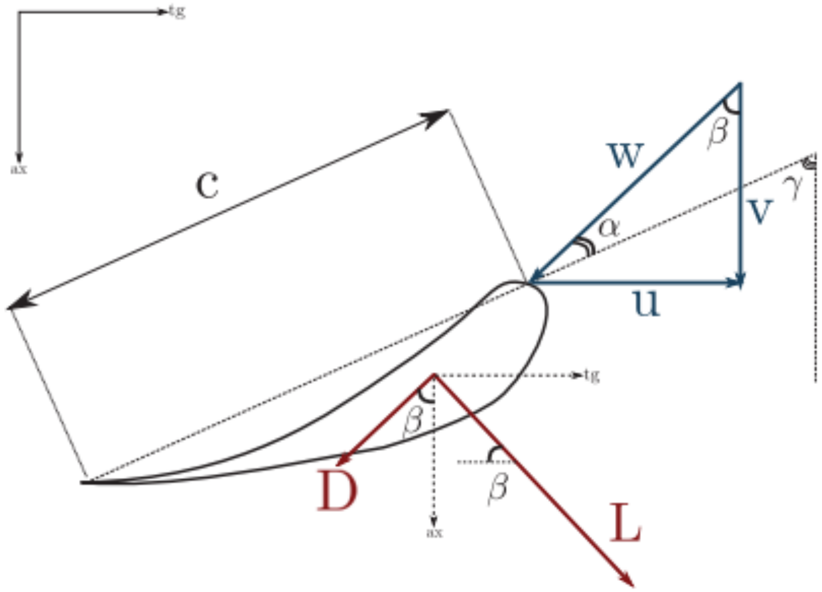


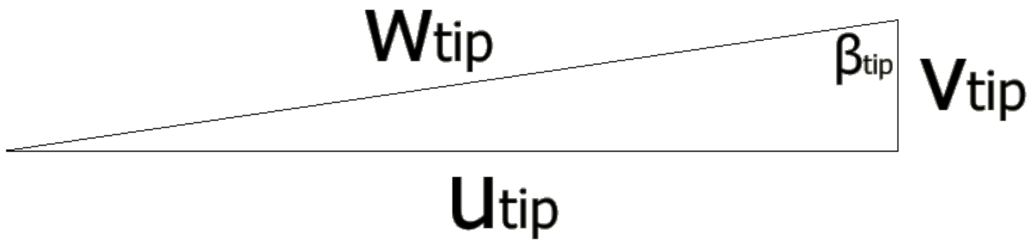


- $R_{hub} = \frac{D}{2} * 20\% = 2.41\,m$
- $u_{hub} = \omega * R_{hub} = 9.59\ ^{m}/_{s}$
- $v_{hub} = v_D = 6.67\ ^{m}/_{s}$
- $w_{hub} = \sqrt{{u_{hub}}^2 + {v_{hub}}^2}$
  $= 11.68\ ^{m}/_{s}$
- $\beta_{hub} = \arctan\left(\frac{u_{hub}}{v_{hub}}\right) = 55.2°$

VELOCITY TRIANGLE

S826-Tip (95% Radius)



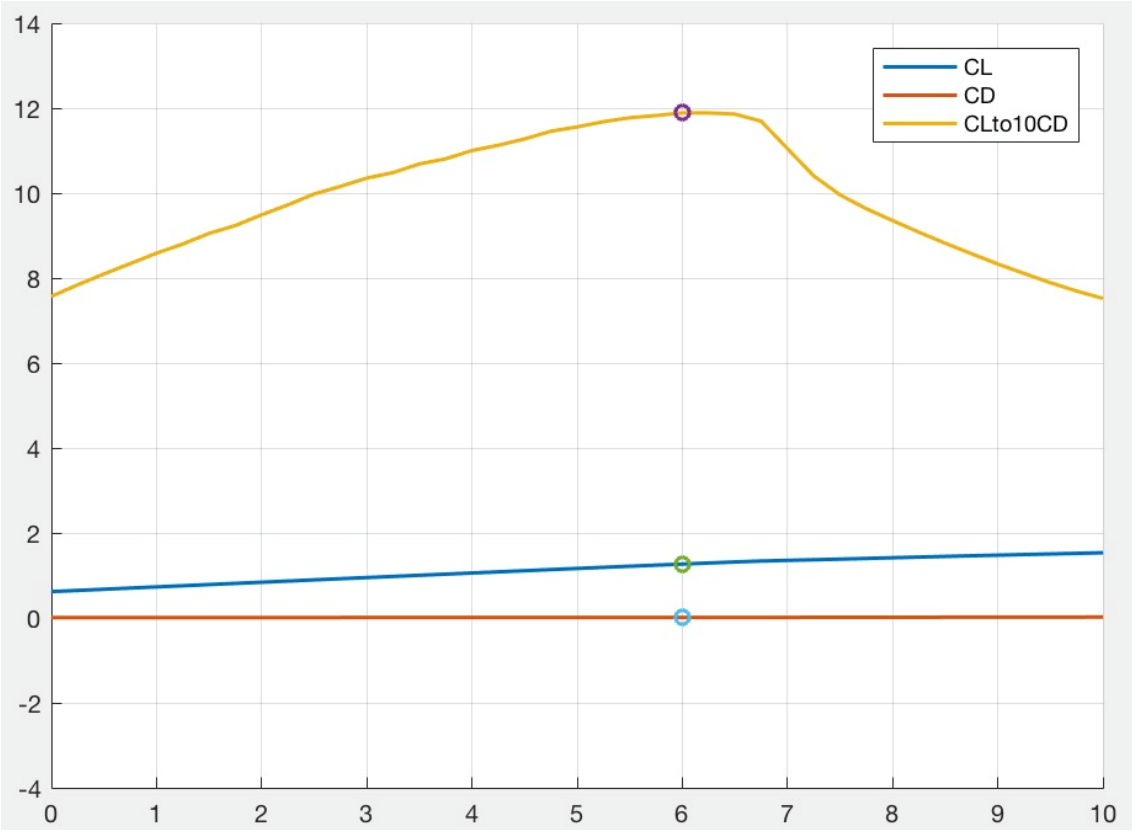


- $R_{tip} = \frac{D}{2} * 95\% = 11.45\, m$
- $u_{tip} = \omega * R_{tip} = 45.56\ {}^{m}/_{s}$
- $v_{tip} = v_D = 6.67\ {}^{m}/_{s}$
- $w_{tip} = \sqrt{u_{tip}{}^2 + v_{tip}{}^2}$

  $= 46.05\ {}^{m}/_{s}$
- $\beta_{tip} = \arctan\left(\frac{u_{tip}}{v_{tip}}\right) = 81.87°$

EVOLUTION

Chord C and crank angle γ – Primary (S825)



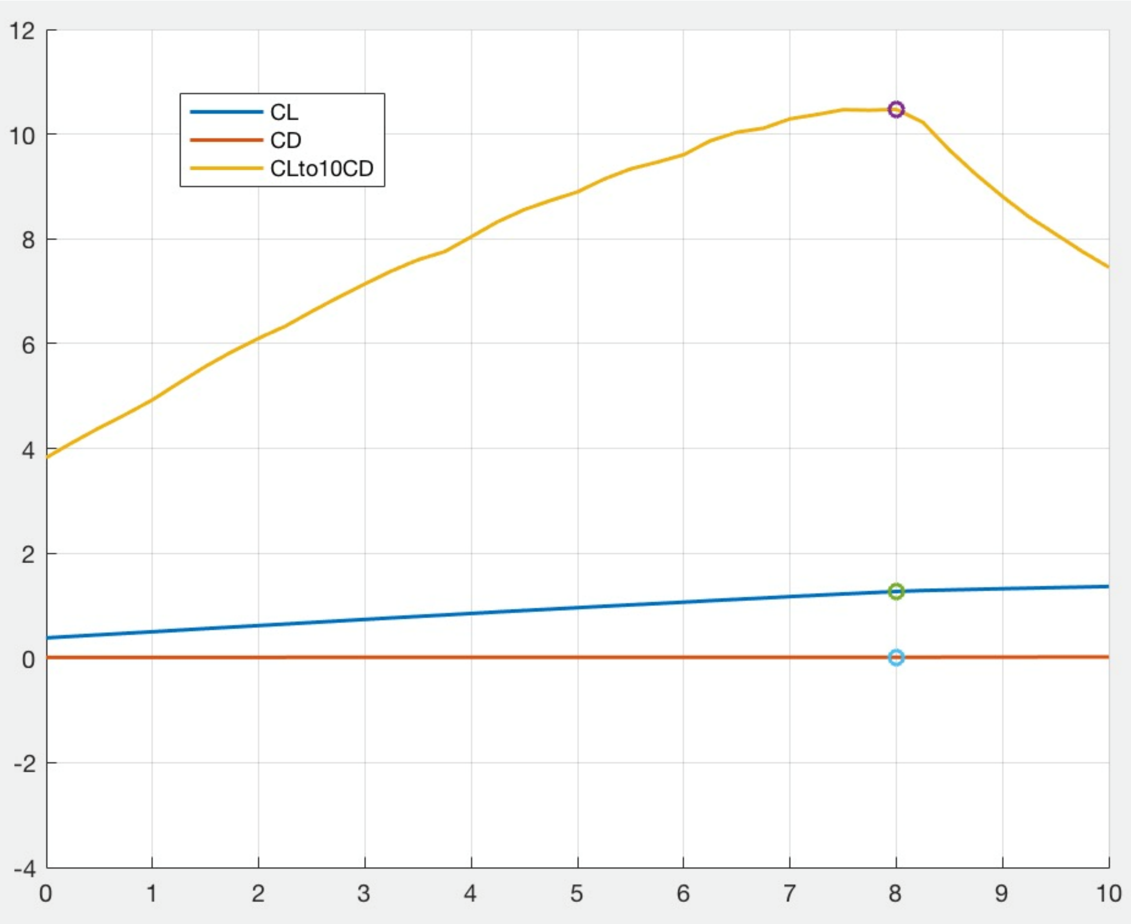
- $N_{bl} = 3$
- $\alpha_{\text{primary}} = 6\,°$
- $C_{\text{L,primary}} = 1.2674$
- $C_{\text{D,primary}} = 0.0107$
- According to the formula

$$c = \frac{\pi r}{N_{bl}} \frac{v^2}{w^2} \frac{8a}{1-a} \frac{1}{(C_L \sin\beta + C_D \cos\beta)}$$

- $C_{\text{primary}} = 1.008\ m$
- $\gamma_{\text{primary}} = \alpha_{\text{primary}} + \beta_{\text{primary}}$
  $= 85.5°$

EVOLUTION

Chord C and crank angle γ – Hub (S814)



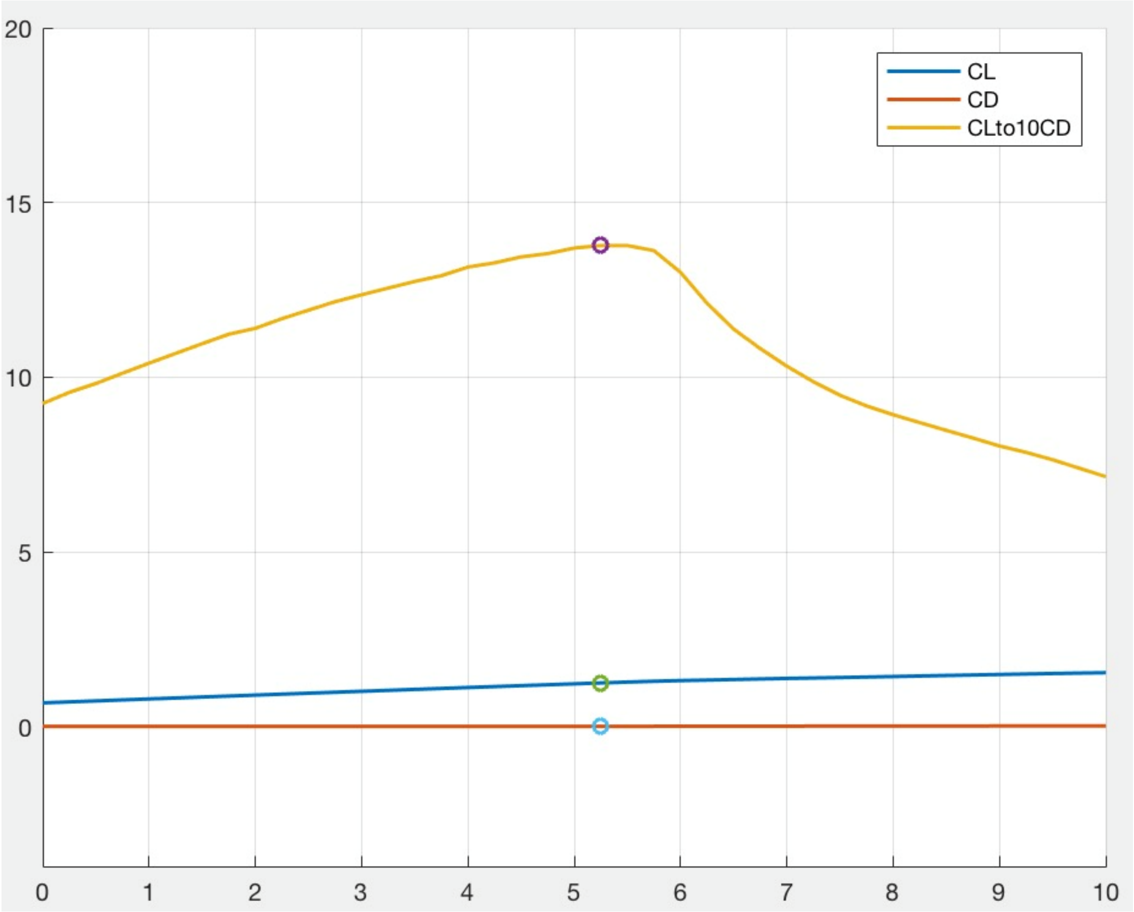
- $N_{bl} = 3$
- $\alpha_{hub} = 8°$
- $C_{L,hub} = 1.2671$
- $C_{D,hub} = 0.0121$
- According to the formula

$$c = \frac{\pi r}{N_{bl}} \frac{v^2}{w^2} \frac{8a}{1-a} \frac{1}{(C_L \sin\beta + C_D \cos\beta)}$$

- $C_{\text{hub}} = 3.1394\, m$
- $\gamma_{\text{hub}} = \alpha_{\text{hub}} + \beta_{\text{hub}} = 63.2°$

EVOLUTION

Chord C and crank angle γ – Tip (S826)

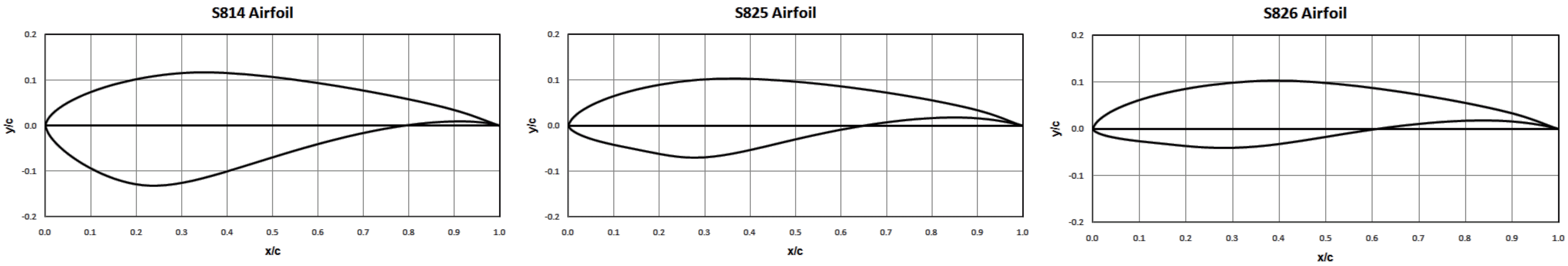


- $N_{bl} = 3$
- $\alpha_{\text{tip}} = 5.25°$
- $C_{\text{L,tip}} = 1.2503$
- $C_{\text{D,tip}} = 0.0091$
- According to the formula

$$c = \frac{\pi r}{N_{bl}} \frac{v^2}{w^2} \frac{8a}{1-a} \frac{1}{(C_L \sin\beta + C_D \cos\beta)}$$

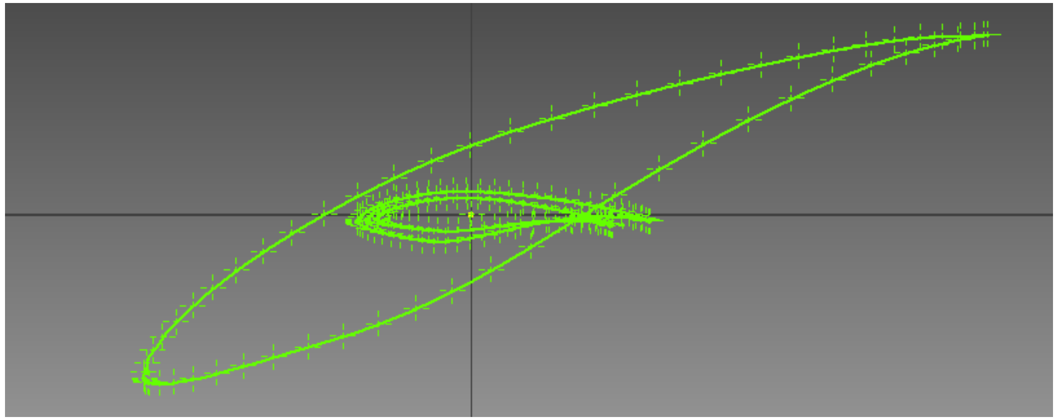
- $C_{tip} = 0.8125\,m$
- $\gamma_{tip} = \alpha_{tip} + \beta_{tip} = 86.92°$

MODELING



- The profile shape of hub, primary and tip respectively

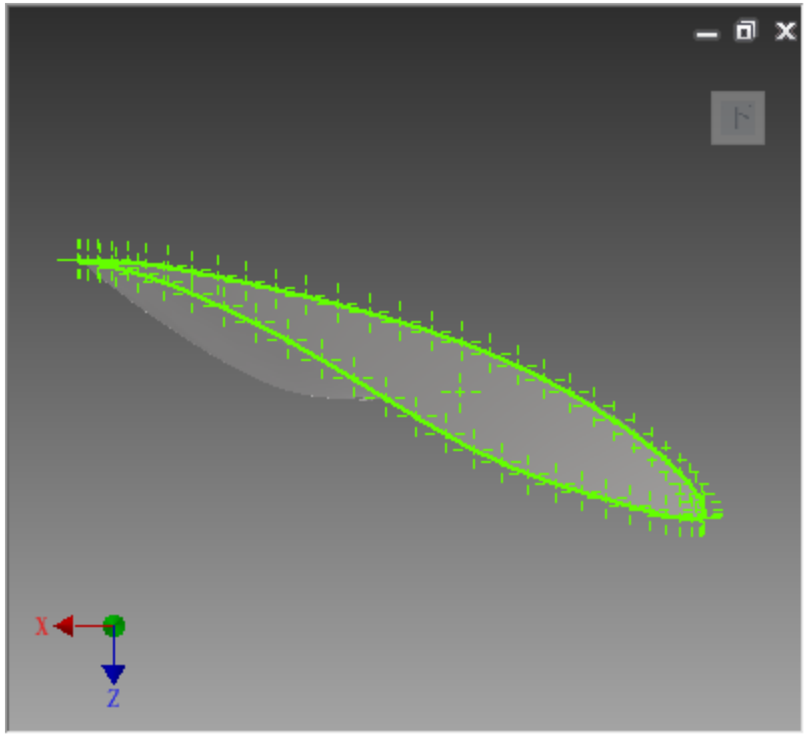
MODELING

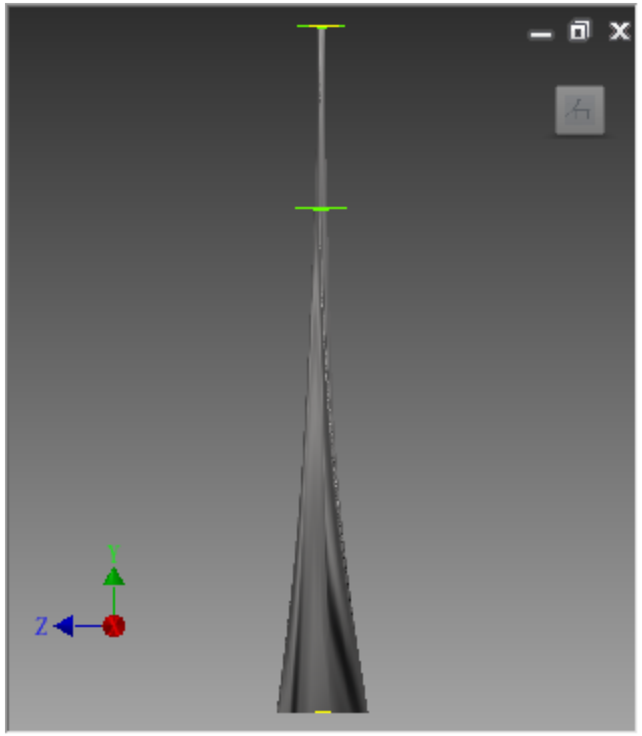


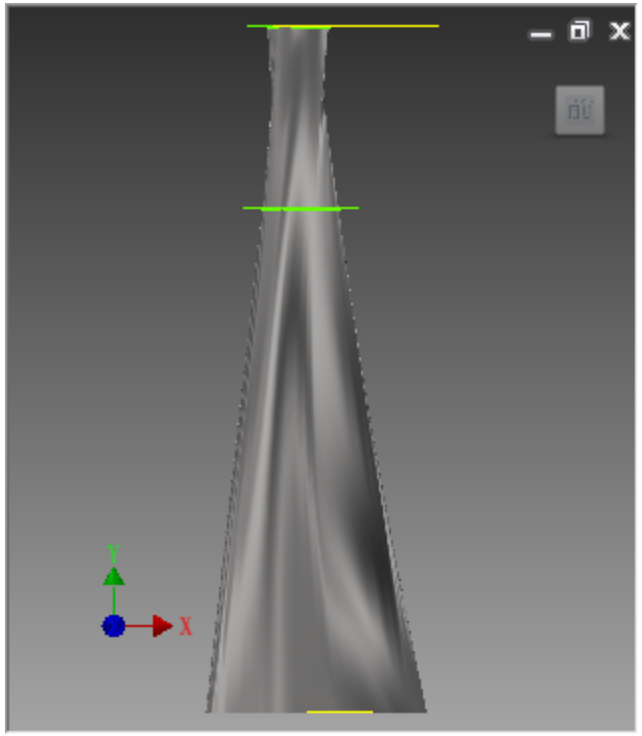
- In order to model the blade, we import the data of profile on three section. Besides, the scale, the geometry center and the angle need to be adjusted.

	HUB	PRIMARY	TIP
SCALE	3.1394	1.008	0.8014
ANGLE	-22.3°	0°	+1.42°
GEOMETRY CENTER-δX	+1695.15	+391.585	+325.777
GEOMETRY CENTER-δY	+24.882	+24.101	+26.024
GEOMETRY CENTER-δZ	-6.63	0	+2.41

MODELING







CALCULATION

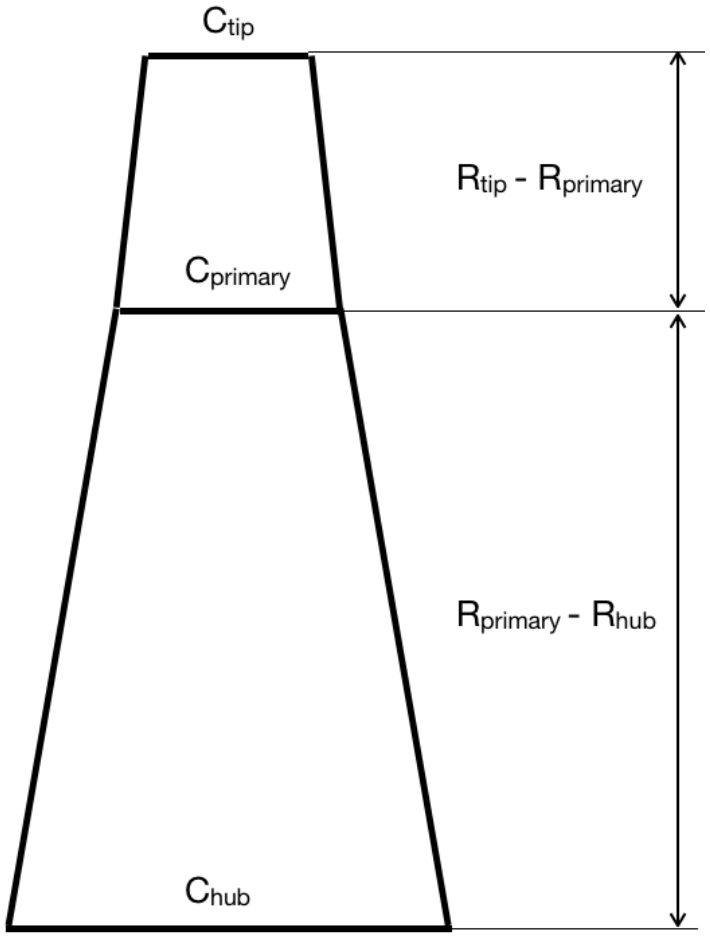
Coefficient of power C_p- 2D

- $P_e = \frac{1}{2} N_{bl} \rho \varpi \int_{R_{hub}}^{R_{tip}} c w^2 (C_L \cos\beta - C_D \sin\beta) r dr$

  $= \frac{1}{2} \rho \varpi \pi V^2 \frac{8a}{1-a} \int_{R_{hub}}^{R_{tip}} \frac{r^2 (C_L \cos\beta - C_D \sin\beta)}{C_L \sin\beta + C_D \cos\beta} dr$
- $P_d = \frac{1}{2} (\rho S_D V_\infty) {V_\infty}^2 = 250.89\ kW$
- $C_p = \frac{P_e}{P_d}$
- In order to calculate the integral for P_e , we use the trapezoidal interpolation and script in Matlab.
- → $P_{e,2D} = 130.57\ kW$
- $C_{p,2D} = 0.52$

Coefficient of power C_p - 3D

- Considering the 3D effects along the blade, we need to do several correction of aerodynamic coefficients.
- $S_{blade} = \int_{R_{hub}}^{R_{tip}} C\, dr \rightarrow S_{blade} = S_{blade}(C_{hub}, C_{primary}, C_{tip})$
- $AR = \frac{h^2}{S_{blade}} \rightarrow AR = AR(C_{hub}, C_{primary}, C_{tip})$
- $C_{L,3D} \approx C_{L,2D}$
- $C_{D,3D} = C_{D,2D} + \frac{{C_{L,3D}}^2}{\pi AR}$
- $C = C(C_L, C_D)$
- Thus we can see that we need to use iteration process to derive coefficient $C_{D,3D}$.



CALCULATION

Coefficient of power C_p- 3D

$i = 0$:
$C_L^{(0)}, C_D^{(0)}, S_{Blade}^{(0)}$

$$AR^{(i)} = \frac{h^2}{S_{Blade}^{(i)}}$$

$$C_L^{(i+1)} = C_L^{(i)}$$

$$C_D^{(i+1)} = C_D^{(i)} + \frac{C_L^{(i)2}}{\pi AR^{(i)}}$$

$$C_D^{(i+1)} - C_D^{(i)} \leq 10^{-6} \ ?$$

Yes !

Output $C_D^{(i)}$

No !

$$C^{(i+1)} = \frac{\pi r}{N_{BL}\pi AR^{(i)}} \frac{V^2}{n^2} \frac{1}{C_L^{(i+1)}\sin\beta + C_D^{(i+1)}\cos\beta}$$

$$C^{(i+1)} \Rightarrow S_{Blade}^{(i+1)}$$

$i = i + 1$

CALCULATION

Coefficient of power C_p- 3D

- The result of iteration of CL & CD

```matlab
c=[];
Nbl=3;v=6.67;w=[20.3,36.58,46.05];a=1/3;
r=[2.41,9.0375,11.45];beta=pi/180.*[70.82,79.5,81.67];
h=r(3)-r(1);h1=r(2)-r(1);h2=r(3)-r(2);
CL=[1.2671,1.2674,1.2503];CD=[0.0121,0.0107,0.0091];
i=1;
while i==1 || abs(CD(i)-CD(i-1))>1e-6
    ci=r./w.^2.*pi./Nbl.*v^2.*8.*a./((1-a).*(CL(i,:)...
        .*sin(beta)+CD(i,:).*cos(beta)));
    c=[c;ci];
    Sblade=(h1*ci(1)+h2*ci(3)+h*ci(2))/2;
    AR=h^2/Sblade;
    CLi=CL(1,:);
    CL=[CL;CLi];
    CDi=CD(1,:)+CLi.^2./(pi*AR);CD=[CD;CDi];
    i=i+1;
end
```

```
>> Effect3D

CL =

    1.2671    1.2674    1.2503
    1.2671    1.2674    1.2503
    1.2671    1.2674    1.2503
    1.2671    1.2674    1.2503
    1.2671    1.2674    1.2503


CD =

    0.0121    0.0107    0.0091
    0.0655    0.0642    0.0611
    0.0650    0.0636    0.0606
    0.0650    0.0636    0.0606
    0.0650    0.0636    0.0606
```

CALCULATION

Coefficient of power C_p- 3D

- Apply the results into the program to achieve Pe & Cp

```
rou=1.1;omiga=3.98;
v=6.67;a=1/3;
Rtip=11.45;Rprim=9.0375;Rhub=2.41;R=[Rhub,Rprim,Rtip];
Ri=linspace(Rhub,Rtip,1000);
CL=[1.2671,1.2674,1.2503];
CD=[0.0121,0.0107,0.0091];
CD_3D=[0.0650    0.0636    0.0606];
beta=[55.2,79.5,81.67].*(pi/180);
CL_interp=interp1(R,CL,Ri,'pchip');
CD_interp=interp1(R,CD,Ri,'pchip');
CD_interp_3D=interp1(R,CD_3D,Ri,'pchip');
beta_interp=interp1(R,beta,Ri,'pchip');
Pei=(0.5*rou*omiga*pi*(v^2)*8*a/(1-a))...
    .*((Ri.^2.*(CL_interp.*cos(beta_interp)-...
    CD_interp.*sin(beta_interp)))...
    ./(CL_interp.*sin(beta_interp)+CD_interp.*cos(beta_interp)));
Pei_3D=(0.5*rou*omiga*pi*(v^2)*8*a/(1-a))...
    .*((Ri.^2.*(CL_interp.*cos(beta_interp)-...
    CD_interp_3D.*sin(beta_interp)))...
    ./(CL_interp.*sin(beta_interp)+CD_interp_3D.*cos(beta_interp)));
 Pe = trapz(Ri,Pei);
 Pe_3D = trapz(Ri,Pei_3D);
 Pd=0.5*rou*456.167*10^3;
 Cp=Pe/Pd;
 Cp_3D=Pe_3D/Pd;
```

```
>> CalPe

Pd =

   2.5089e+05


Pe =

   1.3057e+05


Cp =

    0.5204


Pe_3D =

   1.0414e+05


Cp_3D =

    0.4151
```

CALCULATION

Coefficient of power C_p- 3D

-

	HUB	PRIMARY	TIP
$C_{L,3D}$	1.2671	1.2674	1.2503
$C_{D,3D}$	0.0650	0.0636	0.0606

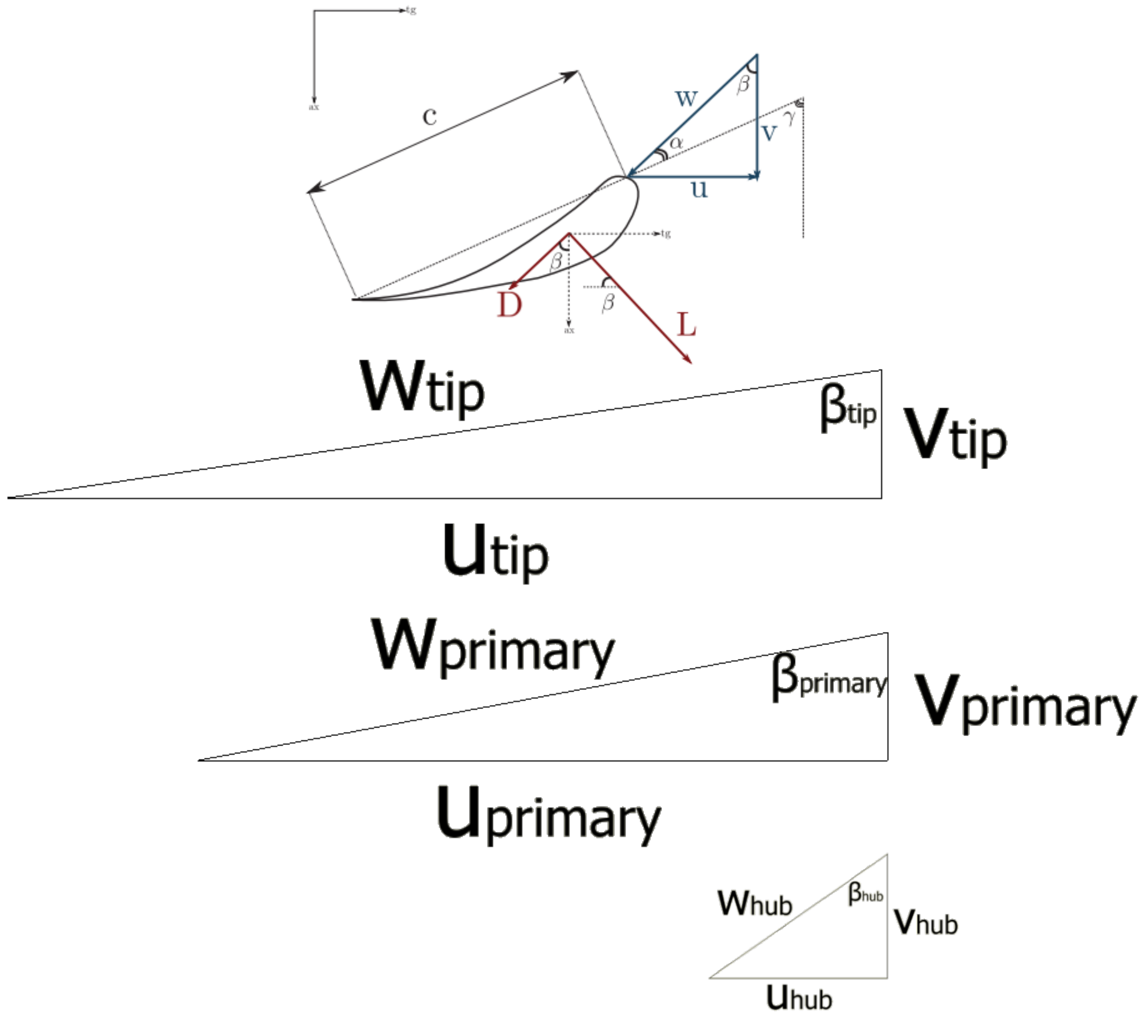
- → $P_{e,3D} = 104.14\ kW$
- $C_{p,3D} = 0.42$

- Comparison of theoretical results and the ones with/without consideration of 3D effect
-

	Theoretical value	Without 3D effect (2D)	With 3D effect (3D)
P_e (kW)	120	130.57	104.14
C_p	0.48	0.52	0.42

VELOCITY TRIANGLE & C_p IN ABNORMAL WORKING CONDITION

V_∞= 8 m/s

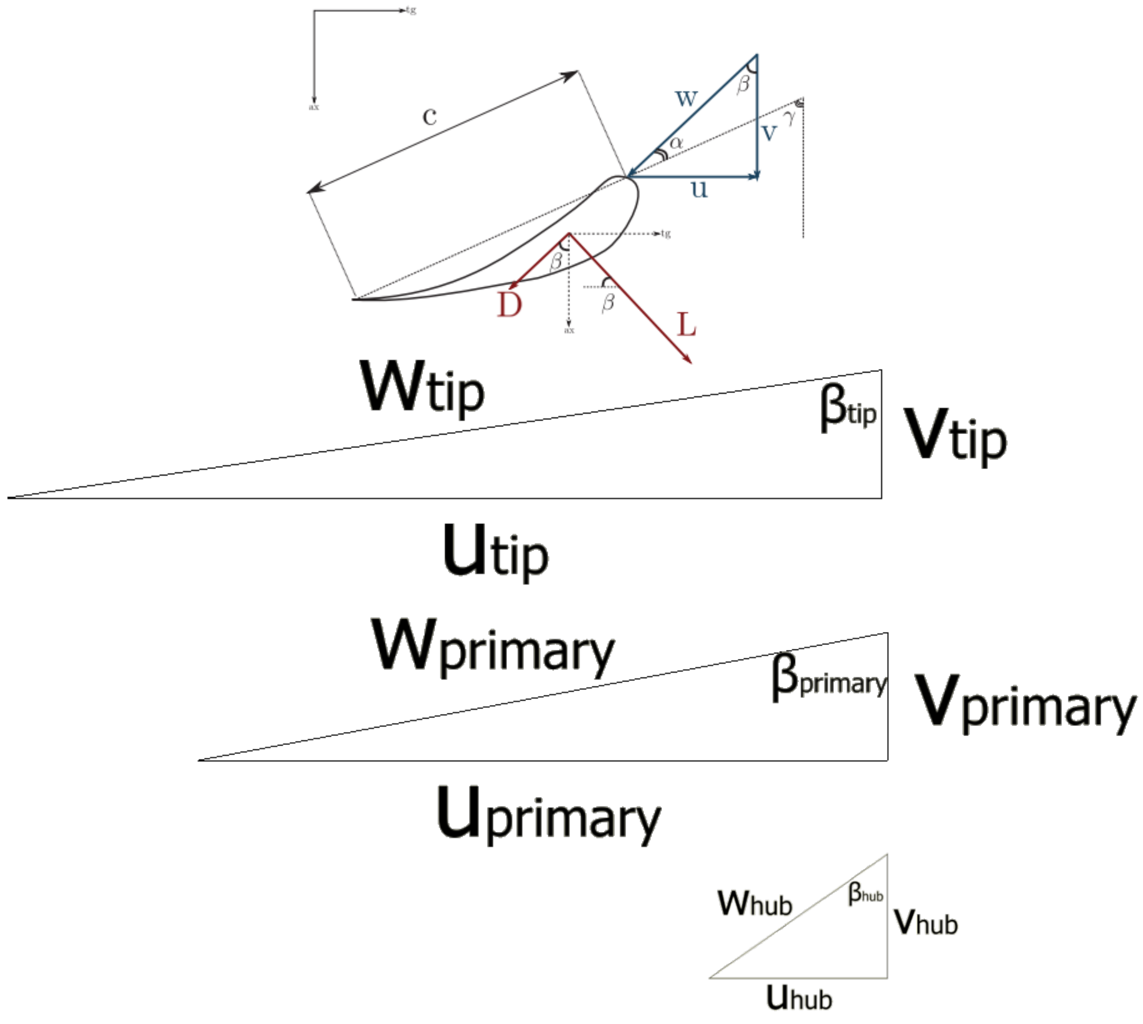


	HUB	PRIMARY	TIP
U	9.59	35.97	45.56
V	5.33	5.33	5.33
W	10.97	36.36	45.87
β	60.94°	81.57°	83.33°

- $C_{p,8} = 0.2865$
- $C_{p,8} < C_{p,10}$

VELOCITY TRIANGLE & C_p IN ABNORMAL WORKING CONDITION

V_∞= 12 m/s



	HUB	PRIMARY	TIP
U	9.59	35.97	45.56
V	8	8	8
W	12.49	36.85	46.26
β	50.17°	77.46°	80.04°

- $C_{p,12} = 0.3668$
- $C_{p,12} < C_{p,10}$

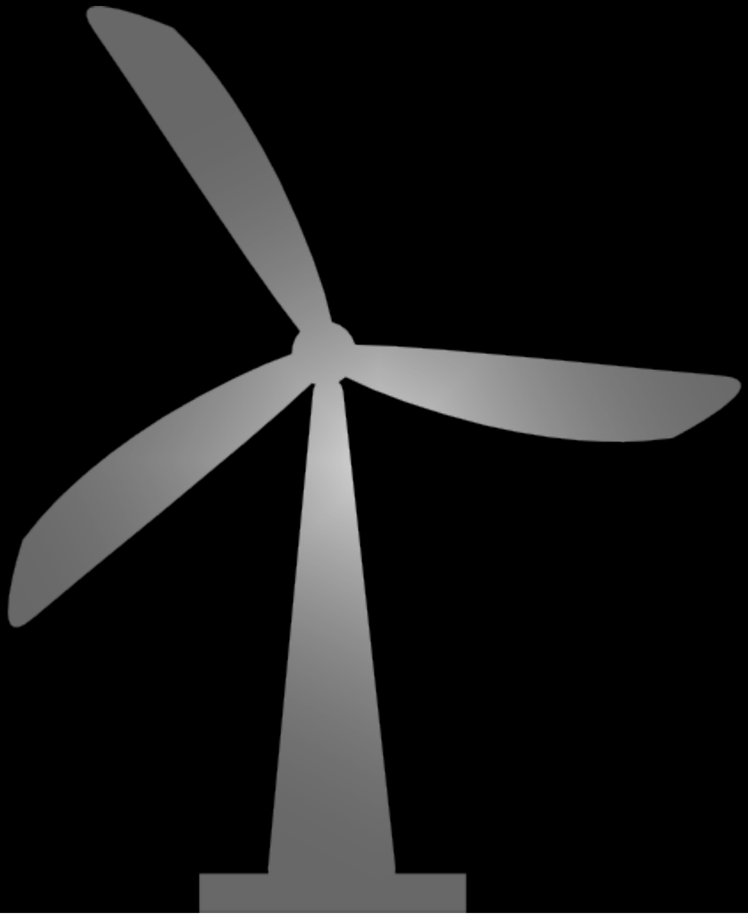
CONCLUSION

- From this project work we have to say we get a paranormal view of how a wind turbine is constructed based on the knowledge of Betz theory, velocity triangles under the help of many professional websites.
- The design of the wind turbine mainly discusses the choice of airfoils and their position along the blade, the coefficient of lift and drag, the coefficient of power and velocity triangular.
- The design of the wind turbine reaches a relatively satisfying result. But due to our limited abilities. There are some deficiencies such as :
  - The choice of blades
  - Theoretical derivation ability

REFERENCE

- http://wind.nrel.gov/airfoils/
- http://airfoiltools.com/airfoil

THANK YOU!



GROUP 2:

CAI ZHONGTIAN 875870
CHEN DELI 875836
JI XIONG 876899
RONG YUXUAN 876754
SHI ZHENYU 875969