

UNIVERSITY OLDENBURG

FORWIND - WIND ENERGY SYSTEMS

Design of Wind Energy Sytems

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September 8, 2016

Contents

1	CIP 1	2
1.1	Total conversion efficiency	2
1.2	Wind Power for nominal electrical power	2
1.3	Rated wind speed	3
1.4	Rotor radius	3
1.5	Rotor area and specific rating	3
1.6	Rotor rated speed & design tip speed ratio	4
1.7	Annual Energy Production	4
1.8	Main aerodynamic properties	4
2	CIP 2	6
2.1	Design your blade according to Betz theory	6
2.2	Design according to Schmitz	7
3	CIP 3 - Performance Curves	9
3.1	Introduction	9
3.2	WT_Perf	9
3.3	3.1,3.2	10
3.4	3.4	13
3.5	3.5, 3.6	14
3.6	3.7,3.8	14
3.7	3.9	15
3.8	3.10	15
4	CIP 4	16
4.1	Task a	16
4.2	Task b	16
4.3	Task c	16
4.4	Task d	18

1 CIP 1

In CIP 1 we were asked to estimate the main parameters of our wind turbine model. In addition we also calculated the airfoil aerodynamics properties and defined the geometry of our blade. The following table shows the side specific conditions and the limitations for the design process of the wind turbine.

Name	unit	value
Airfoil profile set number	-	4
Design wind regime	-	Rayleigh
Target wind regime	-	High
Weibull A-factor (local)	m/s	9
Weibull k-factor (local)	-	2
Rated electrical power	kW	3500
Number of blades	-	3
Cut-in wind speed	m/s	3.5
Cut-out wind speed	m/s	25
Max. tip speed	m/s	82
Max. hub height – reference (*)	m	100
Max. blade length - reference (*)	m	60
Blade root length	m	5
Transmission	-	90

Table 1: Design parameters

1.1 Total conversion efficiency

The total conversion efficiency is used to calculate the amount of energy which can be extracted from the wind flow. Therefore it contains all losses due to mechanical and electrical conversions as the corresponding c_p reference value. The c_p variable describes the maximum amount of energy which can be theoretical extracted from the wind. Taking all these losses into account we have the following equation for the total conversion efficiency:

$$\text{total conversion efficiency} = c_p * \nu_{el} * \eta_{mech} = 0.4705 \quad (1)$$

1.2 Wind Power for nominal electrical power

The rated electrical power of the wind turbine is 3.500 kW. With the total conversion efficiency we computed in the last section we are now able to estimate how much wind power is needed to obtain nominal electrical power.

$$\text{total wind power} = \frac{\text{nominal power}}{\text{total conversion efficiency}} = \frac{3500kW}{0.4705} = 7439.26kW \quad (2)$$

1.3 Rated wind speed

At rated wind speed the turbine is able to extract nominal wind speed. The following equation is used to calculate the power output of the wind turbine. It should be noted that resulting value had to be rounded up.

$$P_{rated} = 0.5 \cdot c_{total} \cdot \rho \cdot \pi \cdot R^2 \cdot V_{rated}^3 \quad (3)$$

where:

P_{rated} = rated electrical power

c_{total} = total conversion efficiency

ρ = density

R = reference max. blade length

V_{rated} = rated wind speed

This equation can be solved for V_{rated} :

$$V_{rated} = \sqrt[3]{\frac{2 \cdot P_{rated}}{\rho \cdot c_{total} \cdot R^2 \cdot \pi}} = 11m/s \quad (4)$$

1.4 Rotor radius

To calculate the rotor radius we used equation (3). Instead of solving for V_{rated} we solved for the blade radius.

$$R = \sqrt{\frac{2 \cdot P_{rated}}{c_{total} \cdot \rho \cdot \pi \cdot V_{rated}^3}} = 54m \quad (5)$$

With a hub diameter of 2.5 meters we end up with a blade length of 52.75 m.

1.5 Rotor area and specific rating

The rotor area is simply the area which is covered by the rotating blades. That leaves us with:

$$A_{area} = \pi \cdot R^2 = 9161m^2 \quad (6)$$

Next we were asked to calculate the specific rating which is defined as:

$$rating = \frac{\text{electrical power}}{\text{area}} \quad (7)$$

We receive 382.06 W/m^2 as specific rating.

1.6 Rotor rated speed & design tip speed ratio

The design tip speed ratio is the ratio between maximum tip speed and rated wind speed of the turbine. The maximum tip speed for the wind turbine is 82 m/s and the calculated rated wind speed is 11 m/s . That leads to a design tip speed ratio λ_d of **7.45**.

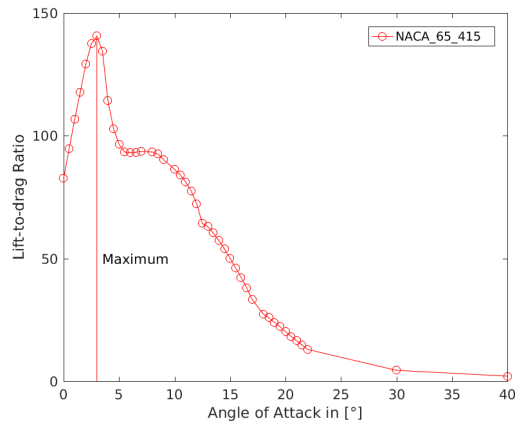
Next we calculated the rotor rated speed. The rotor rated speed in rotations per minute (rpm) is given by:

$$n = \frac{60 \text{ s/min} \cdot \text{max. tip speed}}{2 \cdot \pi \cdot R} = 14.5 \text{ rpm} \quad (8)$$

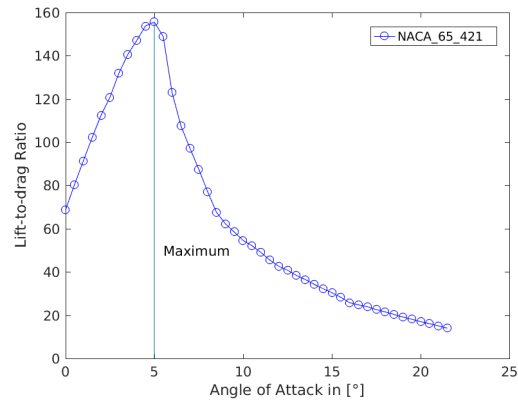
1.7 Annual Energy Production

1.8 Main aerodynamic properties

In order to estimate the design lift coefficient, the angle of attack and the drag coefficient we were given an excel sheet with the rotor design profile data for NACA-64-415 and NACA-64-421. Each sheet consists of 4 columns: angle of attack, lift coefficient, drag coefficient and thrust coefficient. According to the lecture, the optimal lift coefficient is defined as the maximum of the lift-to-drag ratio. Figure 1 shows the lift-to-drag ratio for different angles of attack (AOA).



(a) Lift-to-drag ratio for NACA 65-415



(b) Lift-to-drag ratio for NACA 65-421

Figure 1: Lift-to-drag ratio for different angle of attacks

The figures show that the highest lift-to-drag ratio occurs at low angles of attack. We identified the maximum at 3.0° for NACA 65-415 and 5.0° . For higher angles of attack the lift-to-drag ratio

shrinks. However in practice there is another method to calculate the optimal design lift coefficient. In the further design we defined the design lift coefficient according to the following equation.

$$c_{l_{design}} = \max(c_l(\max[\frac{c_l}{c_d}], 0.8 \cdot c_{l_{max}})) \quad (9)$$

The results are summarized in the following table:

NACA 65-415	α	c_l	c_d	c_m
80% method	10	1.345	0.016	0.071
lift-to-drag method	3.0	0.710	0.005	0.088
NACA 65-421	α	c_l	c_d	c_m
80% method	11	1.255	0.026	0.055
lift-to-drag method	5.0	0.952	0.006	0.092

Table 2: Main aerodynamic parameters

As the 80% method results in a higher lift coefficients for both profiles we selected the corresponding parameters according to the 80% method.

2 CIP 2

In the first part of CIP 2 we designed the blade of the wind turbine. In the lecture we discussed two theories which are used to design the blade geometry. Betz and Schmitz theory both have different approaches to calculate the chord length and the twist angle. For the following steps it is import to keep in mind that the given blade consists of 10 blade elements, which are shown in the following figure.

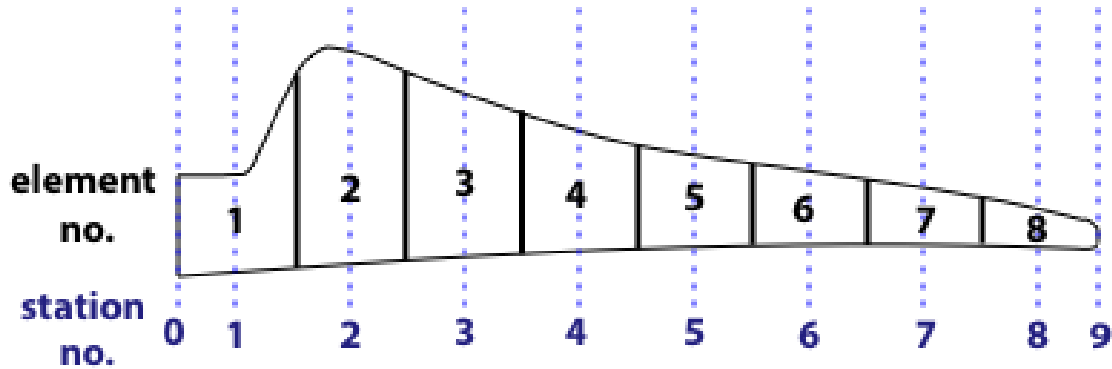


Figure 2: Blade Elements

2.1 Design your blade according to Betz theory

Betz theory estimates that the maximum of power that can be extracted from the wind is:

$$P_{betz} = \frac{16}{27} * P_{wind} \quad (10)$$

To understand why there is a certain limit, consider that if all energy coming from the wind movement through the turbine the speed afterwards would drop to zero and no new wind could get in. The principle of Betz's law is derived from the principles of conservation of mass and momentum of the air stream following through and idealized 'actuator disk' (see figure

If we want to design the blade geometry according to this law, the power from the blade element theory has to equal P_{Betz} . This leads to the following equations which have been used for the further calculation.

Planform:

$$t(r) = 2\pi R \frac{1}{N} \frac{1}{\lambda_a \sqrt{(\lambda_a \frac{r}{R})^2 + \frac{4}{9}}} \quad (11)$$

Twist angle:

$$\alpha(r) = \arctan\left(\frac{2}{3} \frac{R}{r\lambda_a}\right) \quad (12)$$

$$\alpha_{twist} = \alpha(r) - \alpha_a \quad (13)$$

Using the parameters from CIP 1, we calculated the chord length and the twist angle for each blade segment. And overview is shown in table 3.

Station number	1	2	3	4	5	6	7	8	9
Dist.(rotor center) m	4.547	11.141	17.734	24.328	30.922	37.516	44.109	50.703	54.000
Dist.(blade root) m	3.297	9.891	16.484	23.078	29.672	36.266	42.859	49.453	52.750
NACA 65-415									
Chord length m	10.963	5.989	3.957	2.932	2.324	1.923	1.639	1.428	1.342
Twist angle deg	36.725	13.436	5.233	1.228	-1.123	-2.665	-3.752	-4.559	-4.890
NACA 65-421									
Chord length m	11.749	6.418	4.240	3.142	2.490	2.061	1.757	1.531	1.438
Twist angle deg	35.725	12.436	4.233	0.228	-2.123	-3.665	-4.752	-5.559	-5.890

Table 3: Blade design according to Betz theory

2.2 Design according to Schmitz

The blade design according to Schmitz uses the following equations:

Planform:

$$t(r) = \frac{16\pi r}{Nc_l} \sin^2\left(\frac{1}{3}\alpha_1\right) \quad (14)$$

Twist angle:

$$\alpha(r) = \frac{2}{3}\alpha_1 \quad (15)$$

$$\alpha_{twist} = \alpha(r) - \alpha_a \quad (16)$$

where

$$\alpha_1 = \arctan\left(\frac{R}{\lambda_a r b}\right) \quad (17)$$

Using the same approach of the previous section we end up with the following results, shown in table 4.

Station number	1	2	3	4	5	6	7	8	9
Dist.(rotor center) m	4.547	11.141	17.734	24.328	30.922	37.516	44.109	50.703	54.000
Dist.(blade root) m	3.297	9.891	16.484	23.078	29.672	36.266	42.859	49.453	52.750
NACA 65-415									
Chord length m	6.184	5.063	3.671	2.812	2.262	1.887	1.616	1.412	1.328
Twist angle deg	28.589	12.022	4.812	1.054	-1.210	-2.714	-3.783	-4.579	-4.906
NACA 65-421									
Chord length m	6.628	5.426	3.934	3.013	2.424	2.022	1.732	1.514	1.424
Twist angle deg	27.589	11.022	3.812	0.0548	-2.210	-3.714	-4.783	-5.579	-5.906

Table 4: Blade design according to Schmitz theory

The final blade is designed according to Schmitz theory by a combination of profile 1 and profile 2. The first station has got a cylindrical shape. For stations 2-5 the thinner profile is used, for stations 6-8 the thicker profile is used. Table 5 gives more detail about the design rotor blade.

Station number	1	2	3	4	5	6	7	8	9
	Cylinder	65-421	65-421	65-421	65-421	65-415	65-415	65-415	65-415
Blade m	3.297	9.891	16.484	23.078	29.672	36.266	42.859	49.453	52.750
Chord length m	6,628	5,426	3,935	3,014	2,425	1,887	1,617	1,413	1,329
Twist angle deg	27,590	11,022	3,813	0,055	-2,211	-2,715	-3,783	-4,580	-4,907

Table 5: Final blade design according to Schmitz

3 CIP 3 - Performance Curves

3.1 Introduction

In this section we analysed the designed turbine under different pitch angles and tip-speed ratios. The design process of a wind turbine differs from turbine to turbine. In order to compare wind turbines non dimensional coefficients are used. These do not depend on factors like size or wind conditions. The most common coefficient is the power coefficient c_p . Further we used the torque coefficient c_q and the thrust coefficient c_t . These coefficient are defined as:

$$c_p = \frac{P}{0.5 * \rho A v^3} \quad c_t = \frac{T}{0.5 \rho A v^2} \quad c_q = \frac{Q}{0.5 \rho A v^2 * R}$$

where:

c_p = Power coefficient

c_t = Thrust coefficient

c_q = Torque coefficient

p = Power

ρ = Density

A = Area

v = Windspeed

R = Rotorradius

3.2 WT_Perf

To compute the nondimensional parameters a program called WT_Perf is used. WT_Perf uses blade-element momentum (BEM) theory to predict the performance of wind turbines.¹ It also takes different correction algorithms into account, e.g. Prandtl's tip-loss and hub-loss model. WT_Perf can be used from the operating system's command prompt. In order to use WT_Perf we configured the input file by updating the 'Turbine Data' section and implementing the calculated blade geometry. WT_Perf also needs the aerodynamic data of the airfoils. We were able to use the provided data here. Last we defined the range of pitch angle and tip-speed ratio according to the tasks of CIP-3.

The following code-snippet gives an idea of the input file structure:

¹WT_Perf_Users_guide.pdf

1	-----	Turbine Data	-----		
	3		NumBlade:		Number of blades.
3	62.18		RotorRad:		Rotor radius.
	1.25		HubRad:		Hub radius.
5	-3.0		PreCone:		Precone angle , positive downwind.
	5.0		Tilt:		Shaft tilt.
7	0.0		Yaw:		Yaw error .
	100		HubHt:		Hub height.
9	8		NumSeg:		Number of blade segments.
11	RElm	Twist	Chord	AFfile	PrntElem
	3.808	26.530	6.988	1	FALSE
13	11.424	9.594	5.407	1	FALSE
	19.040	2.661	3.832	1	FALSE
15	26.656	-0.866	2.906	1	FALSE
	34.272	-1.967	2.171	2	FALSE
17	41.888	-3.354	1.806	2	FALSE
	49.504	-4.335	1.544	2	FALSE
19	57.120	-5.066	1.348	2	FALSE

3.3 3.1,3.2

As already mentioned we configured the input file according to CIP-3. The generated output file contains values for the power coefficient c_p , thrust T and torque Q . For task 3.2 we wrote a small python-program which examines the data and plots the results for the three different nondimensional coefficient mentioned in the introduction of CIP-3: c_p , c_t and c_q . Since WT_Perf only writes the power coefficient we had to calculate c_t and c_q . Note that the coefficient are functions of $c_t(\lambda)$, $c_q(\lambda)$. The following figures display the results for c_p , c_t and c_q with a tip-speed ratio λ from one to 20 and pitch angles of : 0,5,10,15,20 and 30 degree. The curves are calculated at rated rotor speed (12.59 rpm).

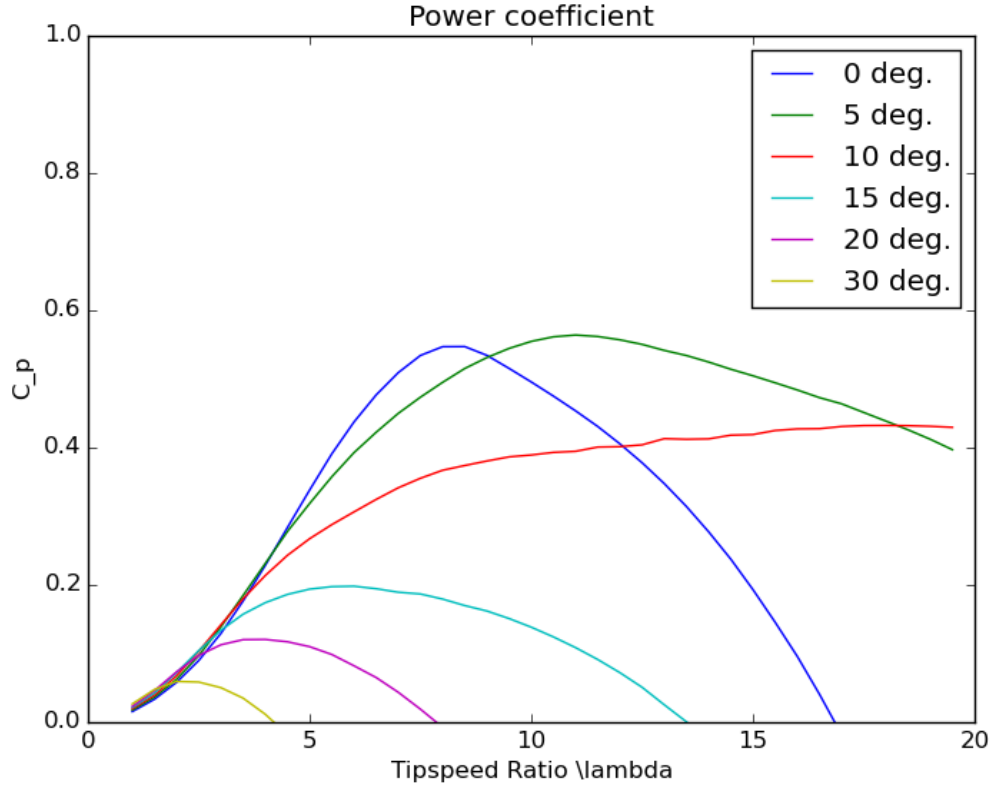


Figure 3: Power coefficient

The $c_p - \lambda$ curve shows different power coefficients at different tip-speeds and pitch-angles. Regarding the maximum for c_p at each curve we identify that they appear at different tip-speed ratios. At pitch angle 5° the maximum c_p is at 0.564 which is very close to the theoretical maximum of 0.592.

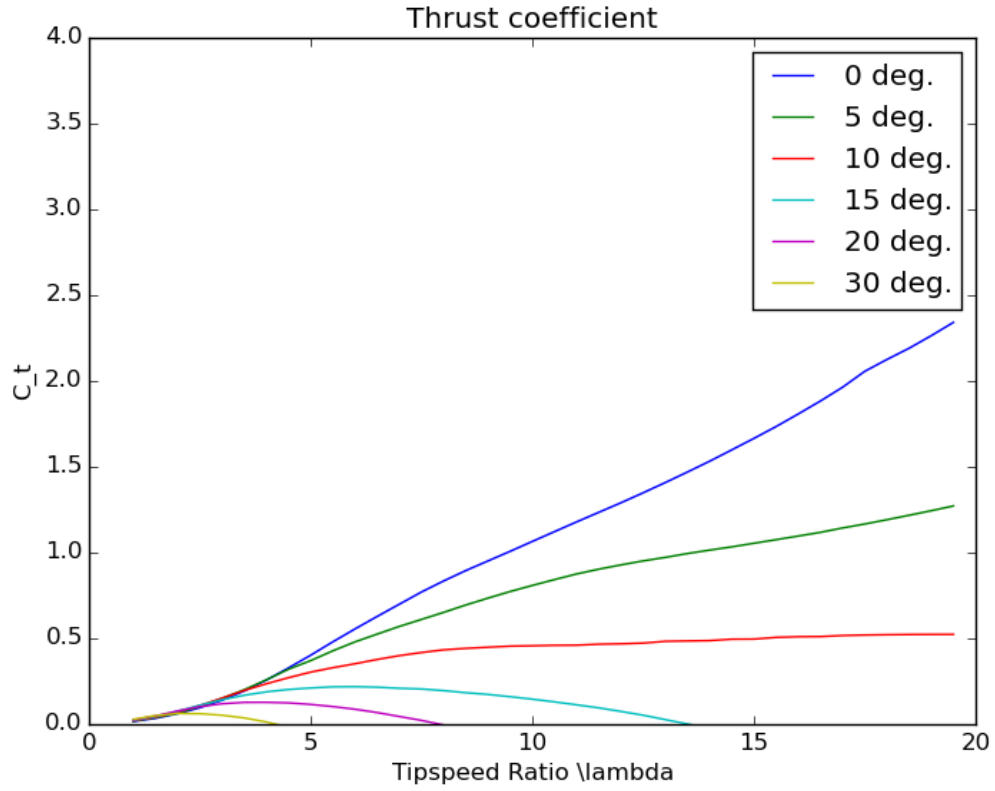


Figure 4: Thrust coefficient

Figure 4 shows the behaviour of the thrust coefficient. From 0° to 10° the thrust coefficient reaches high values. For higher pitch angles the resulting thrust coefficient is significantly lower and is equal to zero for higher tip speed ratios. The thrust is directly applied at the tower and can be decreased by increasing the pitch angle.

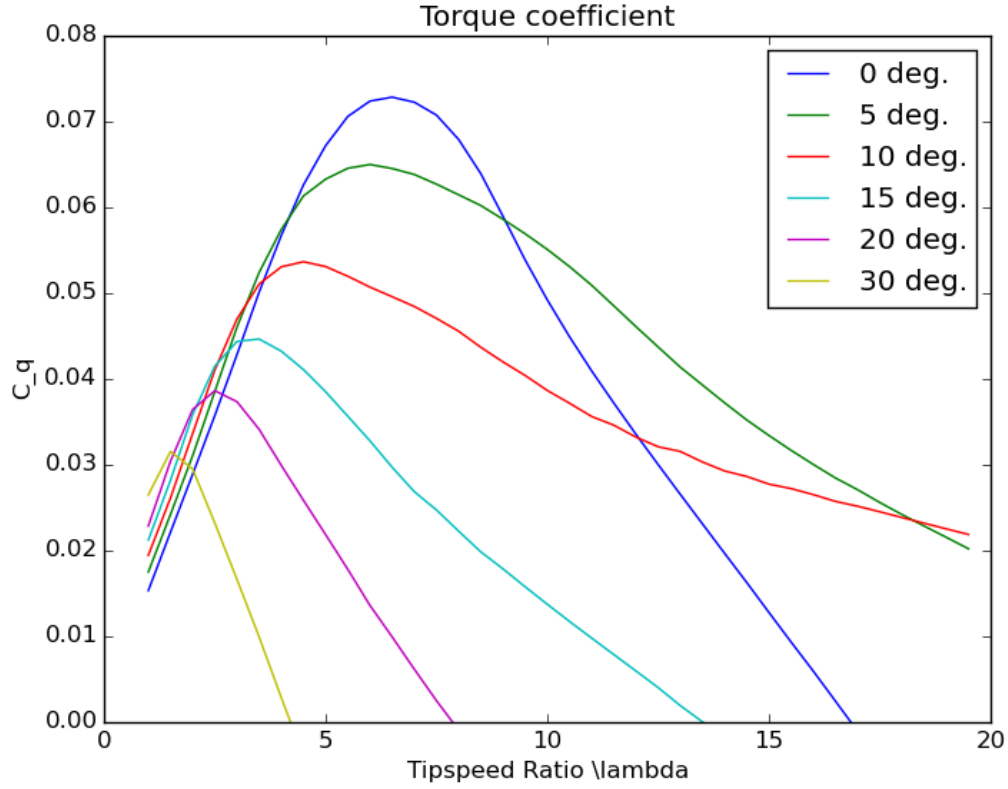


Figure 5: Torque coefficient

Figure 5 shows the torque coefficient for different pitch angles. Compared to the $c_p - \lambda$ the maxima are shifted to the left and decrease with increasing pitch angle.

3.4 3.4

In task 3.4 we were asked to calculate the resulting rotor speed for a rated wind speed of 8 m/s. For the calculation we used our design tip speed ratio:

$$\lambda = \frac{\Omega R}{v} \quad (18)$$

$$n = \frac{60\lambda v}{2\pi R} = 10.07 \text{ rpm} \quad (19)$$

3.5 3.5, 3.6

Again we used WT_Perf to calculate the resulting operation conditions below rated wind speed. The input parameters are: $v = 8$ m/s, design tip speed ratio $\lambda = 8.2$ and rotational speed $n = 10.07$ rpm. The results are shown in the following table:

v m/s	rotor speed rpm	c_p -	c_t -	c_q -	P kW	Power aus WT_Perf
8	10.07	0.544	0.825	0.033	2054.846	

3.6 3.7,3.8

According to Betz, the wind turbine should be able to extract 7618 kW. However the rated power of the wind turbine is lower than the power which could be extracted. Therefore pitching is needed. The resulting c_p can be calculated as follows:

$$c_p = \frac{3500000}{0.5 \cdot 1.225 \cdot \pi \cdot 62.18^2 \cdot 12^3} = 0.272 \quad (20)$$

3.7 3.9

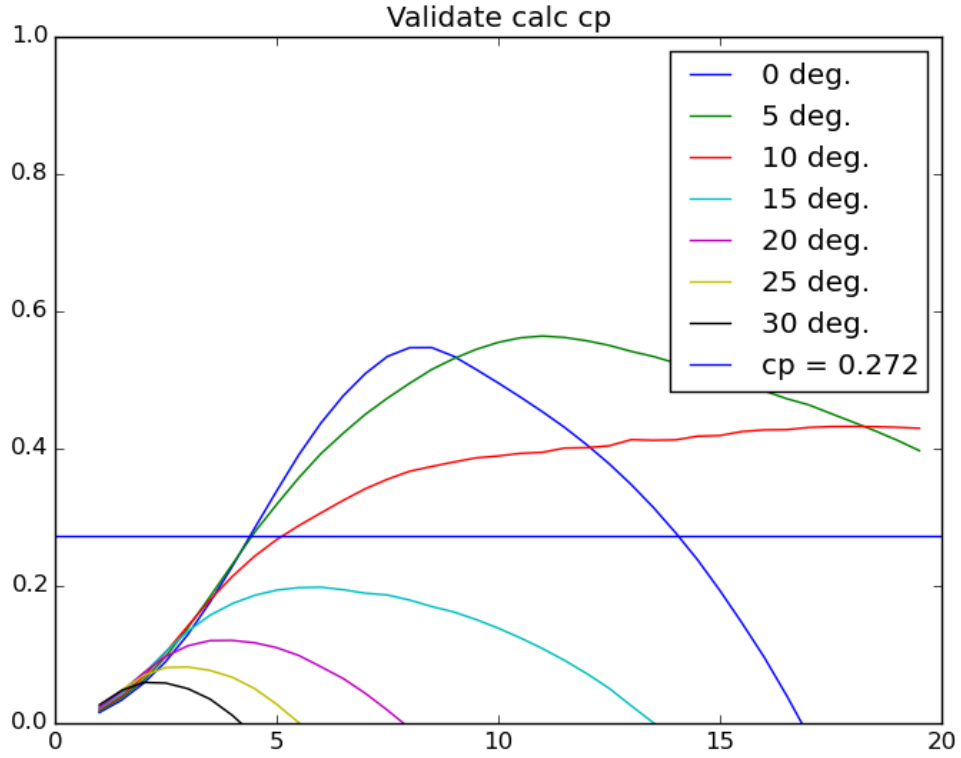


Figure 6: Validation of c_p
The resulting c_p corresponds to a tip speed ratio of 5 with a pitch angle of 10°

3.8 3.10

$$n = \frac{60\lambda v}{2\pi R} = 9.21$$

4 CIP 4

In this part of the Design project a modal analysis for tower design will be carried out and evaluated with respect to economical factors. For this purpose the following parameters are relevant:

$$\Omega_{rated} = 14.5rpm \text{ (rotor rated speed)}$$

$$D = 5m \text{ (tower diameter)}$$

$$E = 211000000000 \frac{N}{m^2} \text{ (elastic modulus)}$$

$$l = 100m \text{ (hub height)}$$

$$m_{top} = 323000kg \text{ (nacelle and rotor mass)}$$

$$\rho = 7850 \frac{kg}{m^3} \text{ (material density)}$$

4.1 Task a

For tower design resonances of excitation frequencies from the rotating blades must be taken into account. The Eigenfrequency of the tower can thus be obtained by adding a 10% safety margin to the rotor rated speed which represents the maximum stationary rotor speed:

$$f_0 = \Omega_{rated} \cdot 1.1 = \frac{14.5}{60} Hz \cdot 1.1 = 0.2658 Hz$$

4.2 Task b

The design range of our turbine is a classical soft-stiff design which results in large wave excitation but allows variable speed turbine design since resonances with tower eigenfrequencies at frequencies lower than rated rotor speed are avoided. There are a few other common design approaches one of which is the soft-soft design where the eigenfrequency lies within the resonance range of the rotor. In this case certain rotor frequencies have to be excluded in order to avoid resonances.

4.3 Task c

The wall thickness t can be computed from the following equations:

$$f_0 \cdot 2\pi = \sqrt{\frac{k}{m_{top} + 0.25m_{tower}}} \quad (21)$$

$$k = \frac{3E\pi D^3 t}{l^3 8} \quad (22)$$

$$m_{tower} = \rho\pi Dtl \quad (23)$$

By substituting Equations (22) and (23) into (21) we obtain the following equality which can be fed into Matlab in order to solve for the only unknown t :

$$0 = \sqrt{\frac{3E\pi D^3 t}{l^3 8 \cdot (m_{top} + 0.25\rho\pi Dtl)}} - f_0 \cdot 2\pi$$

Extract from Matlab code used to solve for variable t :

```

1 t=1;
  func = @(t) sqrt(3*E*pi*D^3*t/(l^3*8*(mTop+0.25*rho*pi*D*t*l)))-f0*2*pi;
3 t = fsolve(func,t);

```

The resulting value for the wall thickness is $t = 0.0318m$. The tower mass is then $m_{tower} = 391730kg = 391.73t$. The material cost for this tower would thus be of 195870 €, assuming a price of 500 €/t. Obviously a thicker tower wall leads to a higher price overall (linear increase). As depicted in Figure 7 a thicker wall leads to a higher Eigenfrequency of the tower as well. However, in this case the relationship is not a linear one due to the exponent of 0.5 in the formula. Hence, a thicker wall results in a higher Eigenfrequency but the increase is only significant for wall thicknesses up to 0.1m. Above that the cost increase does not justify the gain in Eigenfrequency because wall thickness and costs are proportional but the Eigenfrequency is under-proportional.

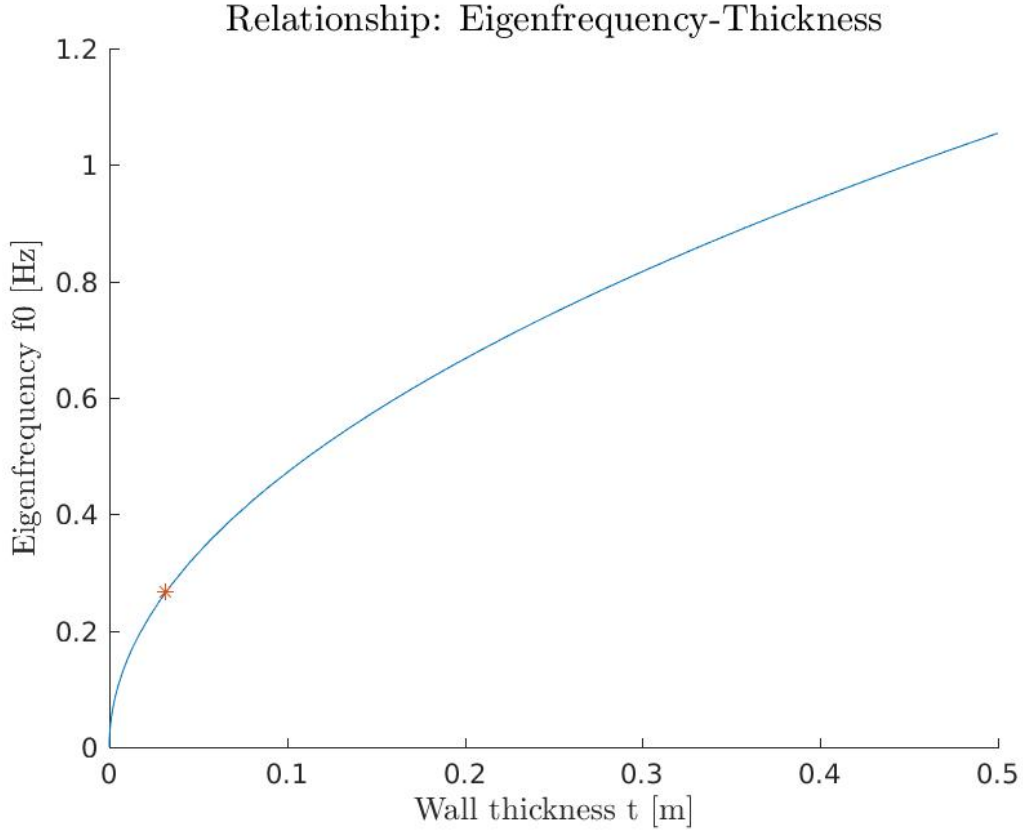


Figure 7: Effect of wall thickness on Eigenfrequency

4.4 Task d

The Campbell diagram is depicted in Figure 8. The red line shows the computed Eigenfrequency of the tower and the circles mark resonance cases for certain rotor speed values due to periodic excitations. For example the dashed blue line (1Ω) represents the 1P excitation (unbalance), the second blue line (3Ω) which represents the periodic excitation caused by a tower shadow of one of the three blades.

The operational range of the rotor with respect to tower Eigenfrequencies must thus be kept within certain limits. By designing the tower wall thickness with adding a 10% safety margin to the rotor rated speed we can be on the safe side and avoid 1P excitations (intersection point of the Ω line with the red line). It must further be excluded during operations that any of the other intersection points occur, e.g. 3Ω line with red line. Some rotational speed ranges must thus be

excluded in operation in order to avoid any resonances. This analysis however only considers tower resonances. A complete evaluation must take into account more resonances as well, e.g. 1st blade edgewise and 1st blade flapwise eigenfrequencies.

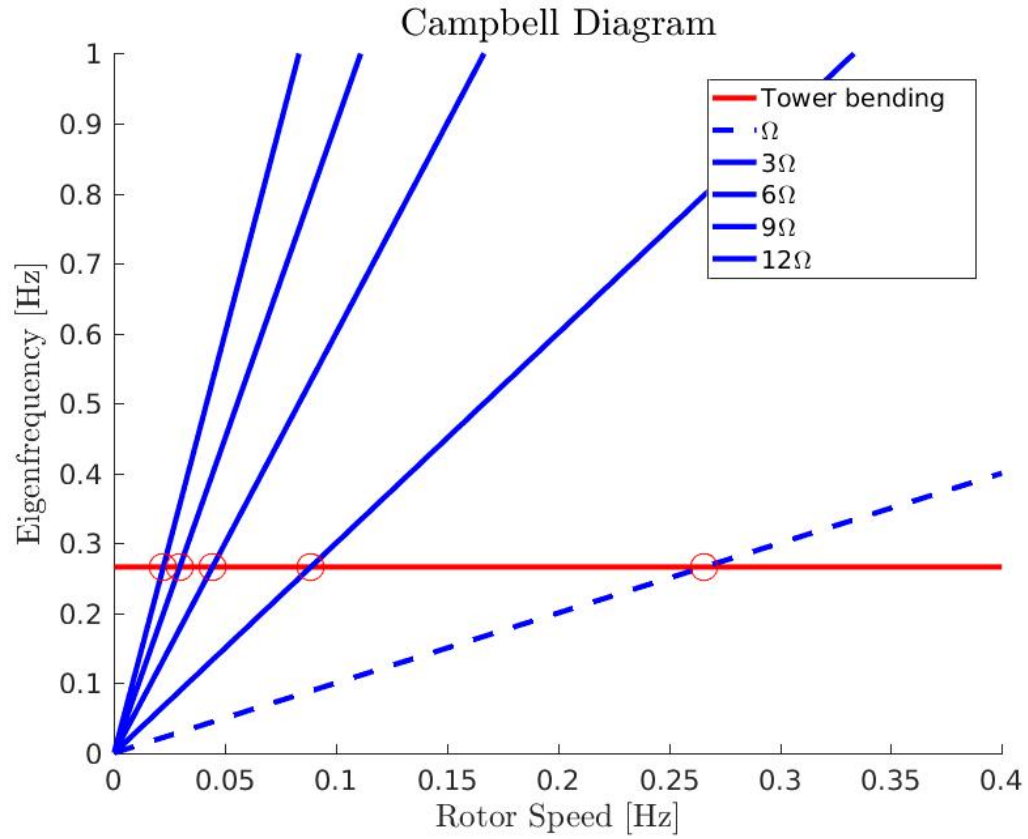


Figure 8: Campbell Diagram