Advanced Wind Energy
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# Wind Energy Fundamentals

Lehrbrief

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# Wind Energy Fundamentals

by

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Oldenburg, September 2017

# Contents

# 1 — The Wind Resource

**Learning objectives**

After processing this chapter you will

- Describe the phenomena behind the origin of the wind.
- Calculate the wind speed at different heights for an specific location.
- List different wind speed measurement devices and describe their working principle, advantages and disadvantages.
- Apply the Weibull and/or Rayleigh distributions to characterize the wind field for a given site.
- Calculate the estimated Annual Energy Production (AEP) of a wind turbine.

In this chapter we are focusing on the ground basis of the wind resource. You will learn the phenomena behind the formation of the wind and which are the differences between the global and local wind patterns. You will also see how the wind changes with height and how the statistic treatment of wind data is done.

Have fun and loosen the study atmosphere with this song!:

*Here comes the sun*. The Beatles
. URL: https://www.youtube.com/watch?v=GwmVfewqu7I.

## 1.1 Wind origins and global wind patterns

**Self-reflection 1.1**


Are you aware of the importance of the sun? Probably your answer is: **Of course! The sun is obviously important**.

Now I want to challenge you to think of 5 things that the sun does for you. Sometimes when we can enjoy some resource almost everyday, it is easy to take it for granted and never think on the magnificent impact it has on our lives. The sun brings us warmth, light, it helps in the production of our vitamin D, it enables photosynthesis and brings us happiness in general (just think of the challenging winter seasons).

In this chapter, we will learn other of the multiple benefits of the sun: its role in the production of the wind resource.

The sun is the driving energy source determining the large-scale climate conditions of the earth. The equator receives a bigger amount of solar irradiation than the poles, producing deferential heating of the atmospheric air. The warmer air from the equator rises due to its density decrease, leaving a zone of low pressure behind. This air travels from the equator to approximately 30° latitude. The low pressure zones left in the equator attract the colder air from higher latitudes, closing the cycle. This process is called the *Hadley circulation*. From 30° to 60° latitude the western wind predominate and the poles characterize themselves by the eastward winds (Figure 1.1) [2] [3].

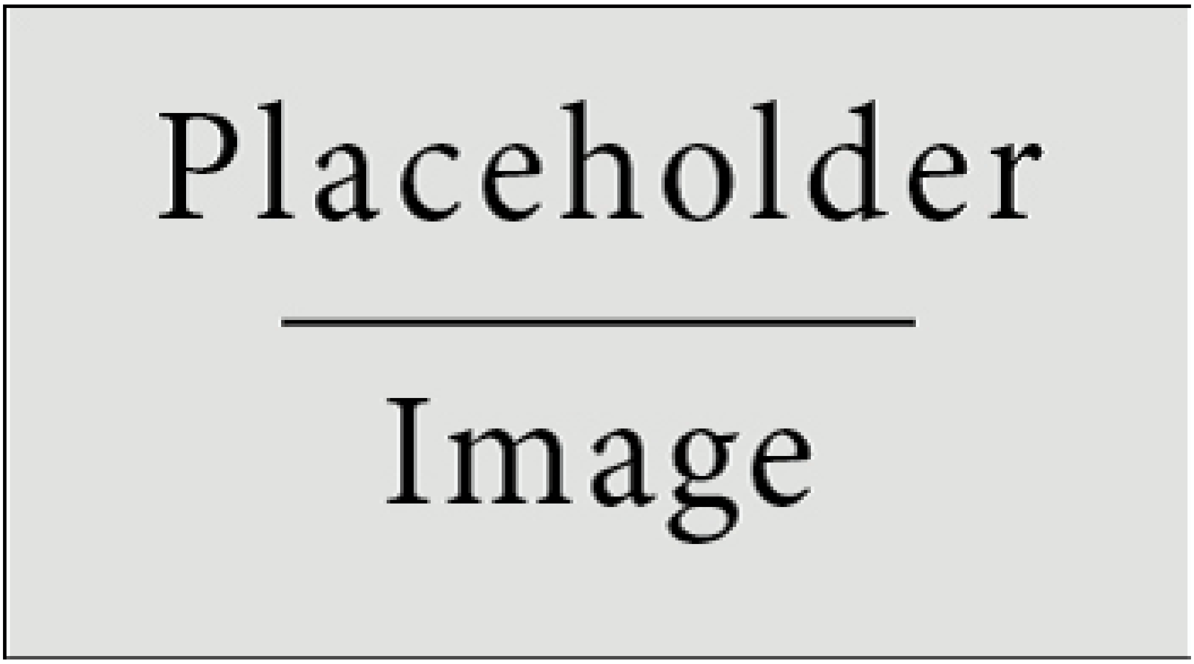



Figure 1.1: Large-scale wind circulation (Source: [2])

### 1.1.1 Geostrophic and surface wind

**Definition 1.1** **Pressure gradient force**: is the force resulting from an imbalance of forces acting on the surfaces of an air volume caused by the pressure gradient. This force vector acts on an air volume between a high-pressure area (cold air with higher density leading to a higher hydrostatic pressure) and a low-pressure area (warm air with lower density leading to a lower hydrostatic pressure) rectangular to the isobars into the direction of the lower pressure. [4].

**Definition 1.2**

**Coriolis force**: is a force which has to be assumed inside of a rotating reference system (e.g. the earth) to explain accelerations that experiences every body during movements, with exception of movement (-components) parallel to the rotation axis of the rotating reference system. These accelerations are not observed from outside of the rotating reference system. In this way of observation the Coriolis force does not have to be assumed.

**Definition 1.3**

**Frictional force**: is generated due to the contact of the wind with the earth's surface. Normally it has an slowing down effect on the wind. This effect would be significant or not, depending on the type of contact surface and it decreases with height [5].

We can identify two broad types of wind: the *Geostrophic* and the *surface* wind. The difference between them lies on the forces acting on the air masses.

The *Geostrophic wind* has no influence of the surface, therefore no frictional force is acting on

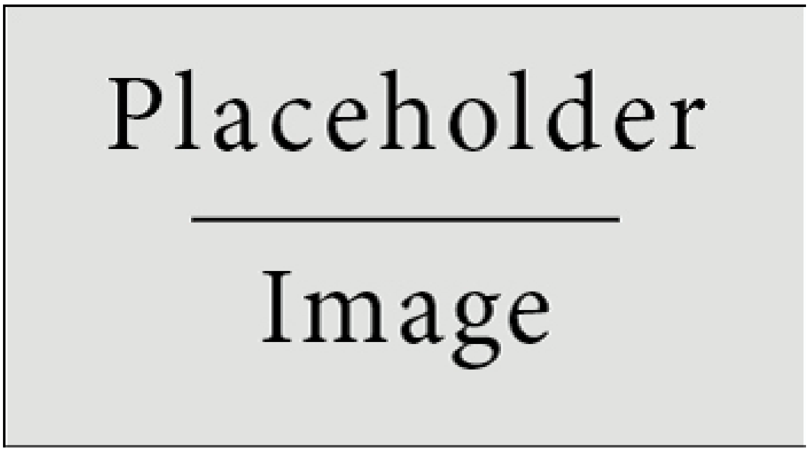



Figure 1.2: The pressure gradient force $F_p$ and and the Coriolis force $F_c$ in balance for the generation of the Geostrophic wind (Source: [6]).

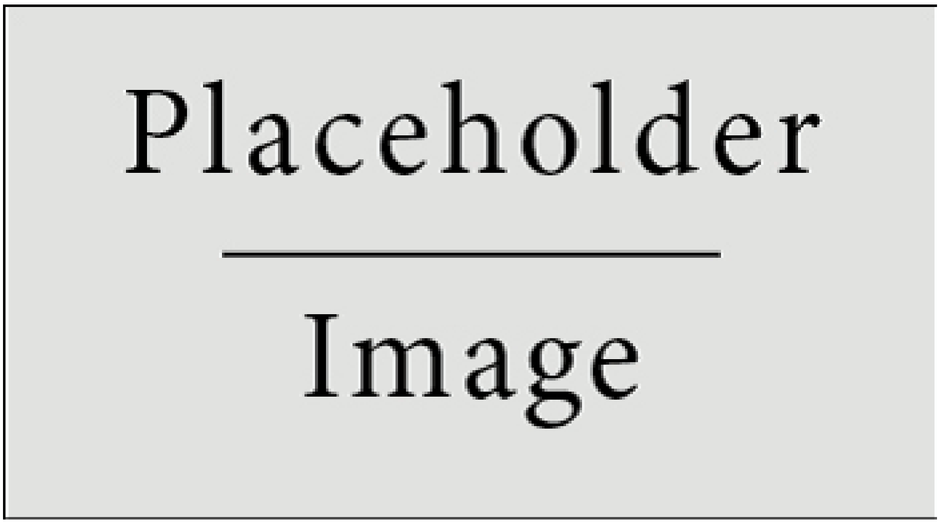



Figure 1.3: Geostrophic wind $G$ traveling parallel to the isobars (Source: [2]).

it. Its direction is governed by the pressure gradient and Coriolis forces. When these two forces are balanced, the wind flows along the lines of constant pressure [3].

On the contrary, the *surface wind* has the influence of the pressure gradient, Coriolis and frictional forces. The pressure gradient force is balanced by the resulting force from the sum of the Coriolis and frictional forces. In general, the surface wind tends to go towards the lower pressure zones [7] [6].

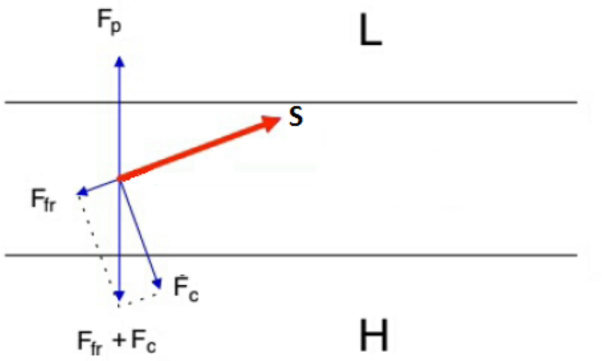



Figure 1.4: Balance of the pressure gradient force $F_p$, the Coriolis force $F_c$ and the frictional force $F_{fr}$ for the surface wins $S$ (Source: Modified from [7]).

## 1.2 Vertical wind profile

**Definition 1.4**

**The boundary layer**: is the nearest portion of the atmosphere to the surface. Hence, it is influence by the characteristics of the terrain, responding to them in small times scales e.g less than an hour.

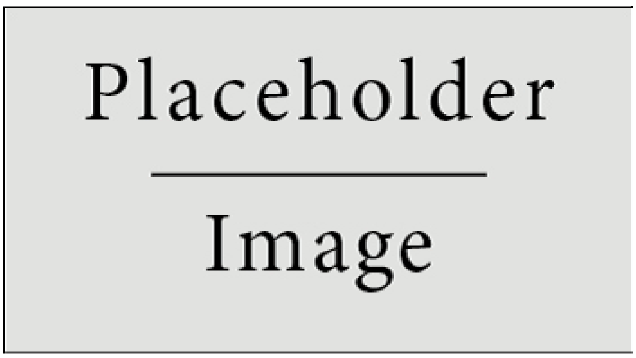



Figure 1.5: Real and mean vertical wind speed profile (Source: Experimental speed profile (van der Tempel, 2006) as cited on [6])

In Figure 1.5, a mean vertical profile is shown in contrast with a real vertical wind speed profile, with the aim of showing the time variation of the wind speed around its mean value. As it can be seen, the wind speed increases with height. the wind speed gradients formed with height generate the *wind shear*. The rate in which the wind speed changes with height depends strongly on the conditions of the surface.

In wind energy utilization, the wind speed along the entire wind turbine should be known, specially at hub height and along the rotor. However, the wind speed is measured in a limited number of heights.

With the purpose to find out the wind speed at different number of heights, the **logarithmic law** , among other mathematical approaches, was developed. It should be kept in mind that there can be uncertainty in the predictions, since this law does not account for complex turbulent flows characteristics. The logarithmic law is shown in Equation 1.1.

**Additional info: Local Winds - Other circulation patterns**

Local winds are produced in a relative small scale and are formed due to the combination of the characteristics of the terrain and the differential heating produced when different types of surfaces are present. Examples of the local winds are the land-see breezes and the mountain-valley breezes [2] [4].


Figure 1.6: land-see breeze (Source: [4]).

The **land-see breeze** is caused by the different rate in which temperature change in the land and the see. During the day, the land heats up faster and stronger than the see, generating a pressure gradient above both of the surfaces. The colder air from the see to the shore. At night, the land cools down faster producing a reverse circulation than during the day.


Figure 1.7: Mountain-Valley breeze (Source: [4])

The **mountain-valley breeze** forms in a similar way than the land-see breeze. During the day, the slopes of the mountains have higher exposure to radiation than the hidden valleys. Therefore, the warm air above the slopes rises, giving room for the colder air from the valley to travel towards the slopes. On the contrary, the valley and the slope of the mountain cool down during the night, along with the air above them, allowing it to sink again in the valley.

$$\frac{U(z)}{U(z_{ref})} = \frac{\ln(z)/\ln(z_0)}{\ln(z_{ref})/\ln(z_0)} \tag{1.1}$$

**Self-reflection 1.2**

Can you imagine why it is so important to know the wind speed at hub height and along the rotor of a wind turbine?. Well, there are to main reasons for it!.:

1) With the mean wind speed at hub height we can predict the energy yield of a wind turbine.

2) Nowadays the rotor of commercial wind turbines are very big, being exposed to the wind shear and uneven forces acting on them. This is one of the most important challenge that wind turbine designers are facing regarding the safety of the structure and the machine in general. Additionally, the wind is time variable which cause significant fatigue on the blades and other components of the turbine.

Imagine a 80 m diameter rotating turbine. Probably the wind speed experienced by a blade when it is in the upper position is bigger than when is in the bottom position. Therefore, the acting forces on the blade could change significantly due to the variable nature of the wind and the rotation of the blade.

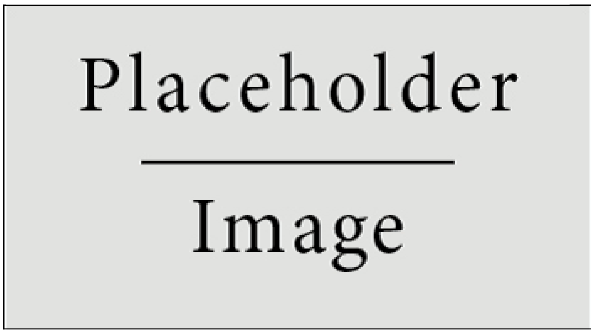



Figure 1.8: Turbine facing uneven wind speed conditions along the rotor (Source: [8])

If the wind speed $U(z)$ in a certain height $Z$ wants to be predicted. A reference measured wind speed $U(z_{ref})$ at the height $z_{ref}$ is needed. The surface roughness length $z_0$ is the parameter that accounts for the characteristics of the surface and corresponds to the height in which the wind speed is zero. Each terrain type has an specific roughness length as shown in Table 1.1.

Additionally, the vertical wind profile can change in its shape due to specific terrain characteristics. In Table 1.2, you can find a some of this terrain effects.

| Type of terrain | $z_0$ [mm] |
|---|---|
| Calm open sea | 0.2 |
| Lawn grass | 8 |
| Crops | 50 |
| Forest and woodlands | 500 |
| Center of cities with tall buildings | 3000 |

Table 1.1: Approximate values of the roughness length $Z_0$ for different types of terrain (Source: [6]).

## 1.3 Wind variations and measurements

The wind speed and direction are fluctuating values that can change in different time scales, e.g. from seconds to annual variations. Even their average values can change from year to year. The reasons for these changes are different for each time scale and are going to be explained further in this section.

The *short-term* variations can go from a few seconds to diurnal variations. The nature of this variations comes from local differential heating (local winds) and the characteristics of the terrain (Table 1.2). The turbulence and gust are short-term variations that have special importance for wind energy utilization, specially they can compromise the safety of the machine. Diurnal variations can change from year to year, as shown in Figure 1.9. Therefore only the general behavior of the variations can be explained, but to predict the amplitude and time span of the variation is a difficult task [3] [6].

The *long term* variations correspond to and annual or inter-annual time span. They relate to the seasonal variations in a certain place. For example, the zone where the measurements from Figure 1.10 were obtained, show that in the first half of the year, there is going to be higher wind speeds than in the second half of the year.

Long term predictions on the variability of the wind are also challenging, since the weather patterns can change from year to year (Figure 1.9). However, as a rule of thumb, one-year measurements are enough to study the annual wind variation patterns from an specific site, with 10 % of accuracy and a confidence level of 90 %.

Due to this variations, it is very important to have long term wind variations to do a proper site assessment. The data from nearby meteorological stations is studied for getting insights of the wind variability, but one year measurements on site are necessary. As a standard in the industry, the measurements are taken with an averaging time of 10 minutes and a sampling rate of 1 second. Tables 1.3 and 1.4 show some of the devices used for measurements of the wind speed on site. The following parameters are derived from the wind measurements:

- The ***mean wind speed*** is important to make a first estimate of the power available in the wind. For a given time period $T$, the mean wind speed $\bar{U}$ can be calculated with Equation 1.2. At this point, it is worth to highlight that Equation 1.2 is used to give only rough estimates. For a parameter that better explains the wind field, it is advisable to calculate

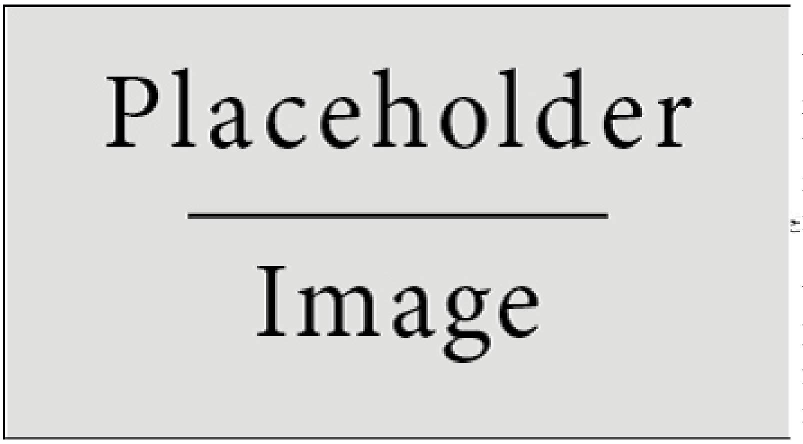
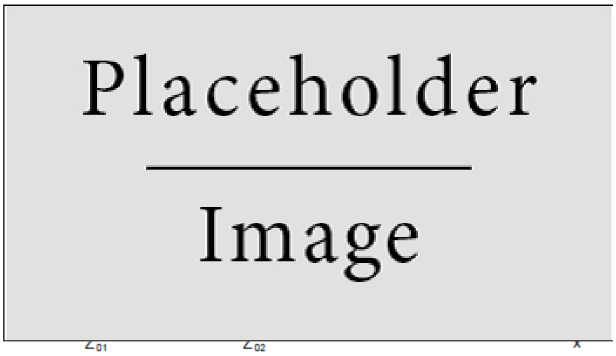
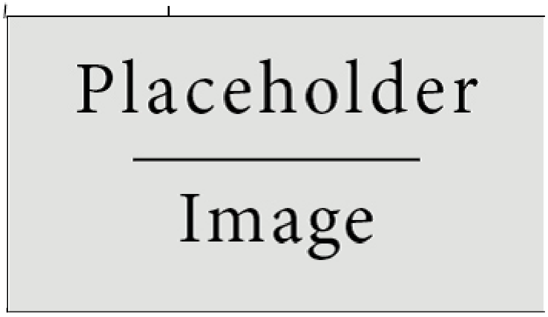
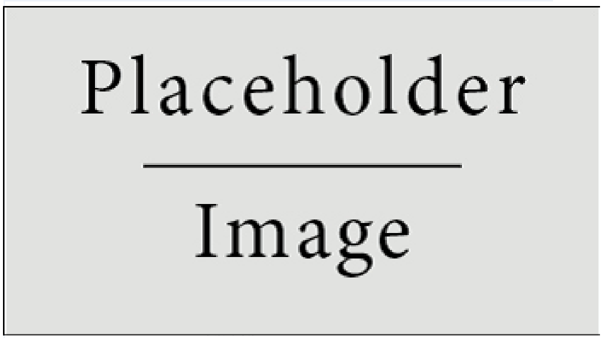
| Characteristics of the terrain | Description |
|---|---|
|  (a) Terrain with obstacles (Source: [6]). | When the wind faces and surrounds an obstacle, a separation bubble behind the object is created. The turbulent flow inside the separation bubble is separated from the outer flow by a shear layer. Researches have tried to estimate the effects of different obstacles as it can be seen in Figure 1.3a. |
|  (b) Influence of the roughness on the vertical profile (Source: [2]). | The wind can pass e.g. from a smooth surface to a very rough terrain, experiencing significan changes on the vertical wind speed profile. |
|  (c) Elevations on the terrain (Source: [2]). | This case is very similar to the case when the wind faces an obstacle. If the elevation has an steep slope, a separation bubble can be formed behind the obstacle. On the contrary, if the slope is gentle, the wind can experience some acceleration. |
|  (d) Depressions on the terrain (Source: [6]). | Depressions are parts of the terrain with lower height than their surroundings. Some examples of depressions can be valleys and canyons, where the wind is channeled and accelerated. |

Table 1.2: Influence of different terrain characteristics on the wind profile

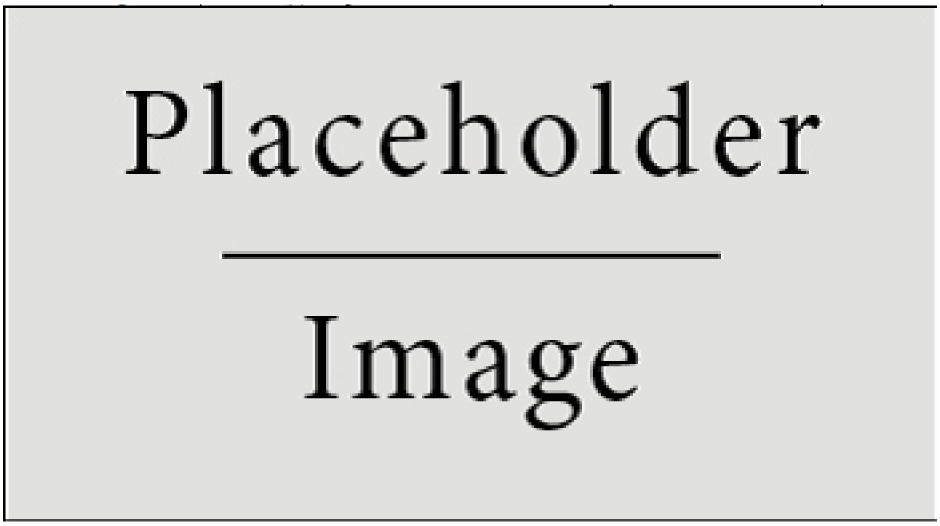



Figure 1.9: Average diurnal variations for different years in Casper-Wyoming (Source: (Hister and Pennel, 1981) as cited on [6])

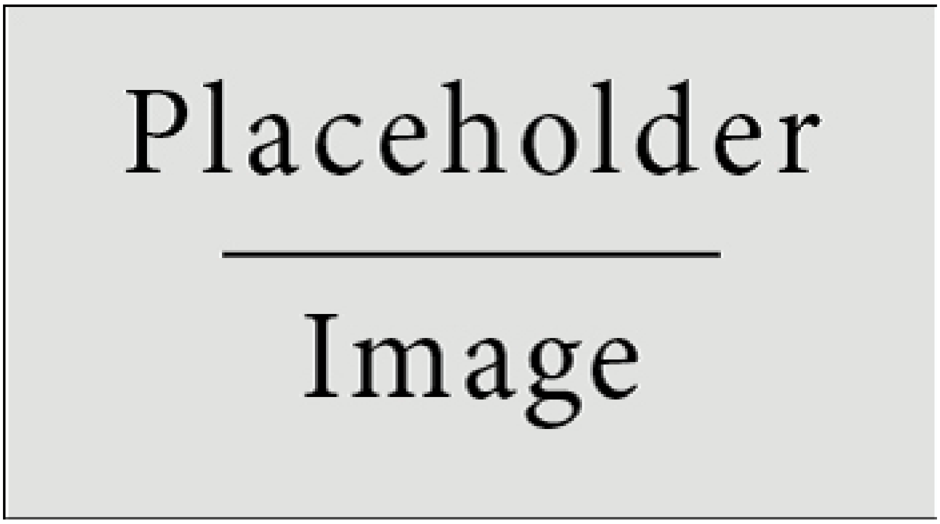



Figure 1.10: Monthly average of the wind speed - Seasonal variations (Source: (Hister and Pennel, 1981) as cited on [6])

the mean wind speed using one of the statistical models used for this purpose e.g. the Weibull Distribution.

$$\bar{U} = \frac{1}{T}\int_0^t v(t)dt \tag{1.2}$$

- The ***standard deviation*** of the measurements is used to estimate the variability of the data set. It explains how far are the individual wind speed measurements from the mean wind speed. It is calculated with Equation 1.3.

$$\sigma_U = \frac{1}{n-1}\sum_{n=1}^{n}(U_n - \bar{U})^2 \tag{1.3}$$

- The ***Turbulence intensity*** is an indication of the level of turbulence in a determined time span. It is found with the Equation 1.4.

$$I = \frac{\sigma_U}{\bar{U}} \tag{1.4}$$

- The ***Wind direction distribution*** is an important parameter for e.g. planing of wind farms to avoid unwanted shading effects. For the purpose of having a complete characterization of the wind direction, three types of wind roses exist.

**Example 1.1 — Operation principle of the cup anemometer.**
The cup anemometer works due to the drag forces that are produced when the wind is surrounding the cups. The most simple cup anemometer has only two semi-spherical cups. As shown in Figure 1.11, if the cups are placed perpendicular to the wind direction, the wind is going to "see" two different shapes. While the concave shape of the upper cup is facing the wind, the wind is seeing the convex shape of the bottom cup.

As you might know, when a body is immerse in a moving fluid, drag force is produced. its magnitude is fully dependent on the shape of the body. The reason behind this is that each body has a determined drag coefficient. This is the basic principle that is used in this anemometer. The drag force produced with the convex side of the cope is smaller than the one produced with the concave side. This results in a moment on the rotational axis making the device to rotate.

Complementarily, The magnitude of the drag forces are dependent on the wind speed as well. Therefore, the higher the wind speed, the stronger the forces and the faster the rotation of the anemometer.

The wind speed rose shows the mean wind speed for the different wind directions. The wind frequency rose shows the predominant direction of the wind for the site. finally, the wind energy rose shows the energy distribution dependent on the wind direction (Figure 1.12).

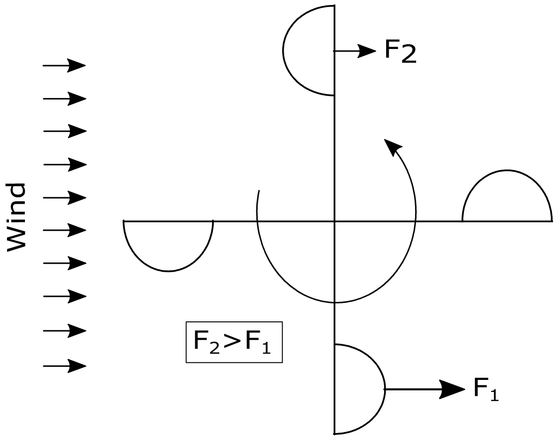



Figure 1.11: Working principle of the cup anemometer

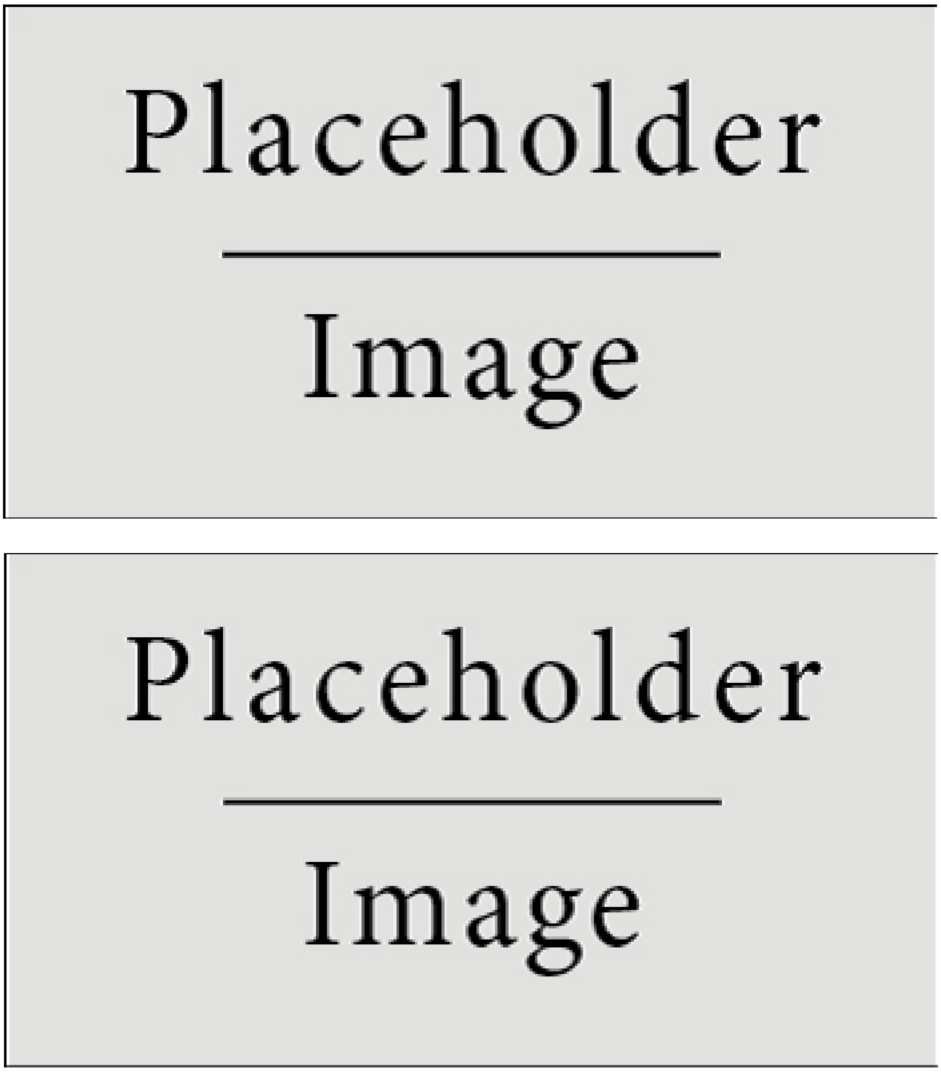



Figure 1.12: Types of wind roses (Source: [2])

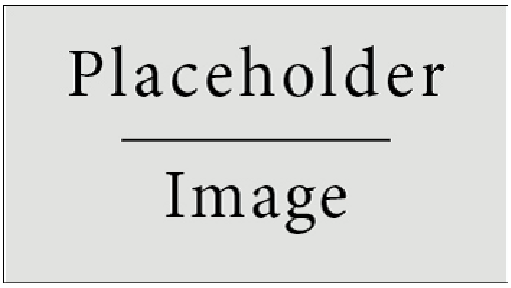
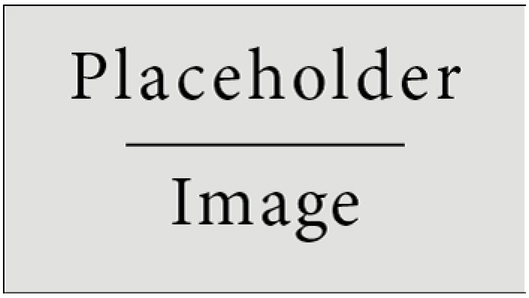
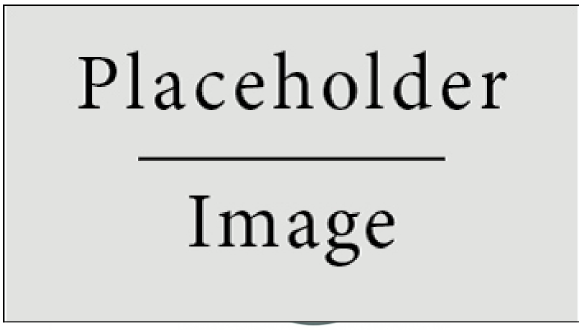
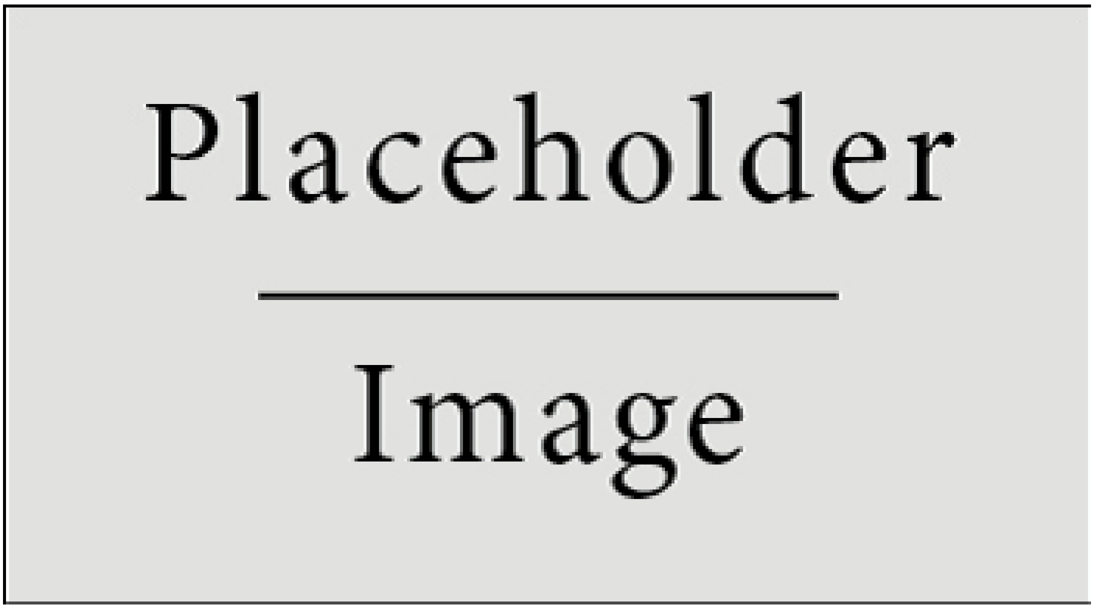
| Example of intrusive sensors | Description |
|---|---|
| <br><br>(a) Prandlt tube (Source: [9]). | **Operating principle:** Static $P_s$ and total pressure $P_T$ are measured. Taking into account that $P_T = P_s + P_d$. The dynamic pressure ($P_d = \rho U^2/2$) can be calculated from the measurements and the wind speed $U$ can be derived.<br>**Advantages:** Simple device, no moving parts.<br>**Disadvantages:** Foreign material can go inside the tube, disrupting the reading. |
| <br><br>(b) Cup anemometer (Source: [10]). | **Operating principle:** See example 1.1.<br>**Advantages:** Simple device, omni-directional.<br>**Disadvantages:** Its inertia prevents it to sense fast changes in the speed, moving parts wear out, overestimation of the wind speed when non-zero vertical speeds are present, low temporal resolution. |
| <br><br>(c) Ultrasonic anemometer (Source: [11]). | **Operating principle:** The device measures the time taken by a sound pulse from one transducer to another. The wind speed can be calculated using the mentioned time, the speed of sound and the distance between the transducers.<br>**Advantages:** No moving parts, sensible to fast changes in speed and to low wind speed, high temporal resolution, 3D information can be obtained dependent on the model.<br>**Disadvantages:** Expensive, the suporting structures can create wakes affecting the data. |
| <br>(d) Sphere anemometer (Source: [12]). | **Operating principle:** The flexible tube deflects due to drag forces. The deflection of the anemometer is measured, which is proportional to the wind speed (Research in progress in Forwind).<br>**Advantages:** Simple device, spheres with different drag coefficients can be used.<br>**Disadvantages:** Possible damage due to fatigue, temporal resolution up to resonance frequency (this can be an advantage when compared to other anemometers). |

Table 1.3: Intrusive anemometers

**Example of non-intrusive sensors**




(a) Non-intrusive anemometers (Source: [13]).

**Operation principle**: Light pulses (for the LiDAR) or sound pulses (for the SoDAR) are sent to the air, which are back scatter by aerosols. The moving particles in the wind produce a back signal with a Doppler shift, which is proportional to the wind speed.

| SoDAR | LiDAR |
|---|---|
| **Advantages:** Ground based, measurements in different heights, 3D wind speeds can be measured.<br>**Disadvantages:** Expensive, complex device, background noise can affect the measurements, the speed of sound is affected by temperature and humidity (corrections might be needed). | **Advantages:** Ground based, measurements in different heights, 3D wind speeds can be measured, insensitive to sound interference.<br>**Disadvantages:** Expensive, complex device, light pulses can affect the human visual health. |

Table 1.4: Non-intrusive anemometers

## 1.4 Wind statistics

For practical reasons, the data set of wind speeds and directions is treated sadistically.

In the case of the wind speed,intervals (*bins*) are defined and the times that the wind speeds corresponding to a certain interval are counted. This information is summarized in a *frequency density distribution* like the one shown in Figure 1.13. The wind speed intervals are normally of 1 m/s.

It has been proven that there are two statistical models that nicely fit the shape of the frequency distribution: the *Weibull* and *Rayleigh* distribution functions. Both functions are quite practical, since just few parameters are needed to describe the wind field.

To calculate the frequency density distribution function $fd$ according to ***Weibull***, Equation 1.5 is used, where $k$ is the shape factor and $A$ is the scaling factor.

$$fd\,(U) = \frac{k}{A}\left(\frac{U}{A}\right)^{k-1}\,exp\left(-\left(\frac{U}{A}\right)^{k}\right) \tag{1.5}$$

**Self-reflection 1.3**

Are the terms frequency $f$ and frequency density $fd$ the same thing?...

No. When we refer to frequency we are addressing the number of times the data falls in a certain interval. On the other hand, frequency density refers to the fraction or percentage of data that falls in a certain interval. Therefore:

$$f = fd\,\Delta U \tag{1.6}$$

Where $\Delta U$ is the size of the interval. In the case of the wind speed, $\Delta U$ would be 1 m/s. Notice then that the units for $fd$ are [1/(m/s)] , whereas $f$ can be dimensionless.

Each site has particular $k$ and $A$ values, which also change with height (Figure 1.15). On one side, the $k$ factor represents the uniformity of the data. Values from 0 to 4 are typical for this parameter. When $k$ is high means that the wind speed values are close to the mean wind speed. On the contrary, when $k$ is small the values show more deviation respect to the mean wind speed (Figure 1.14).

On the other side, $A$ determines how high is the peak and how "wide" is the curve.

Additionally, the cumulative distribution is also used (Figure 1.16), which shows the portion of times the data falls in or under a given wind speed. It is calculated as the integral of the Weibull distribution function for $fd$ (Equation 1.7).

$$F(U) = \int_0^U fd(U)\,du = 1 - exp\left(-\left(\frac{U}{A}\right)^{k}\right) \tag{1.7}$$

Furthermore, it is possible to predict the mean wind speed using the Weibull parameters, with

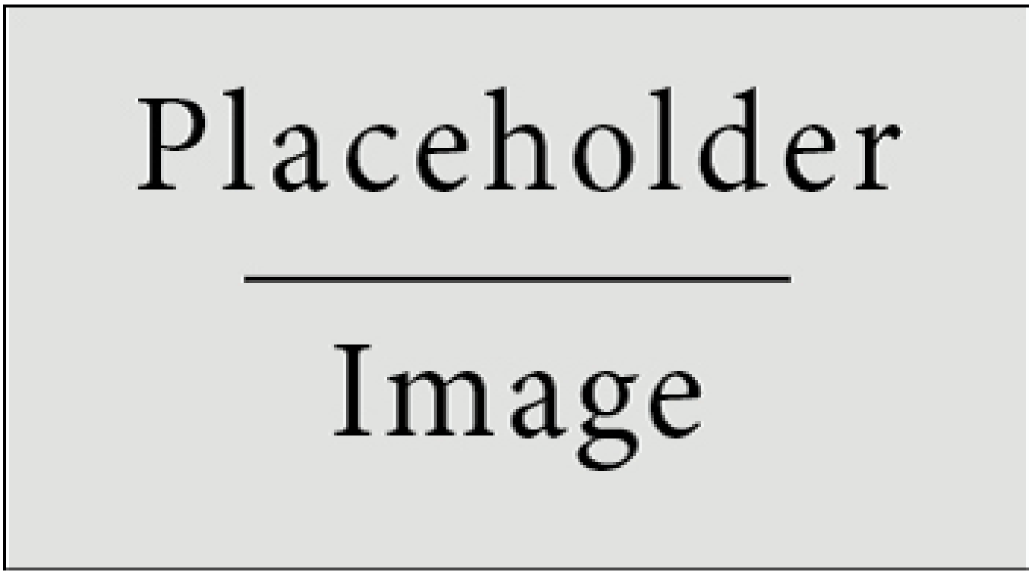



Figure 1.13: Example of a frequency distribution (Source: [2])

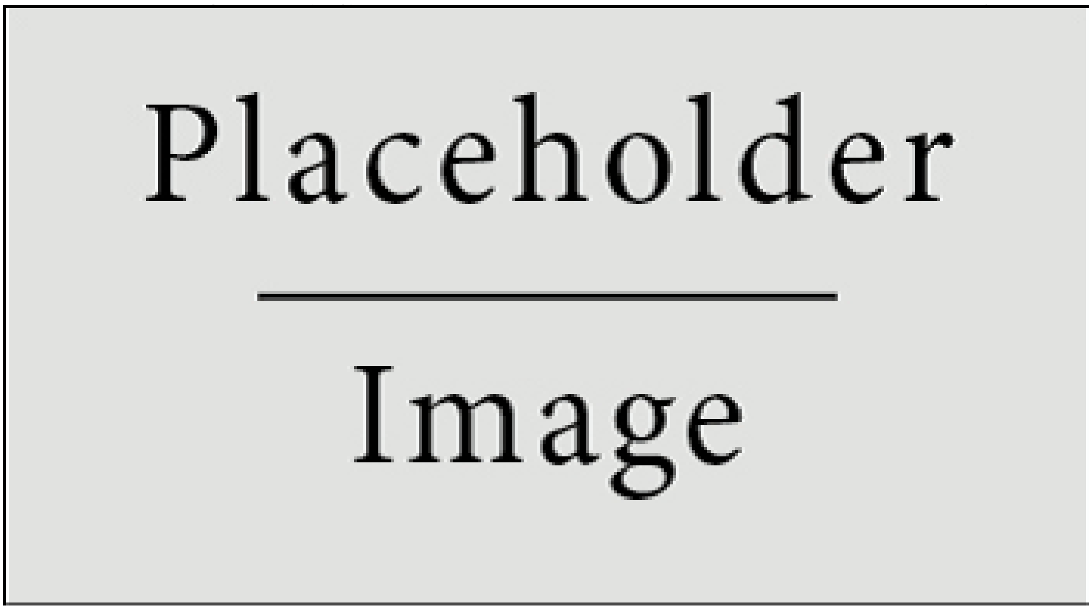



Figure 1.14: Influence of the shape parameter $k$ in the Weibull distribution (Source: [3])

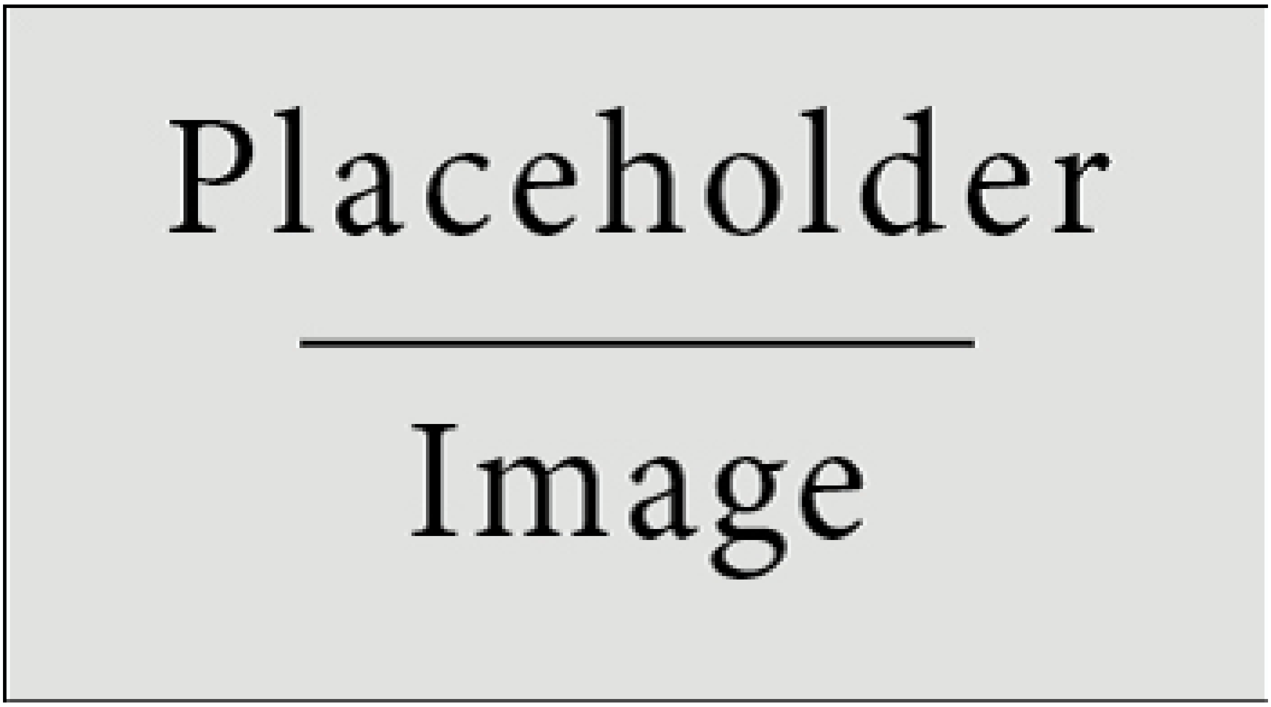



Figure 1.15: Change of the scale parameter $A$ and the shape parameter $k$ with height (Source: [2])

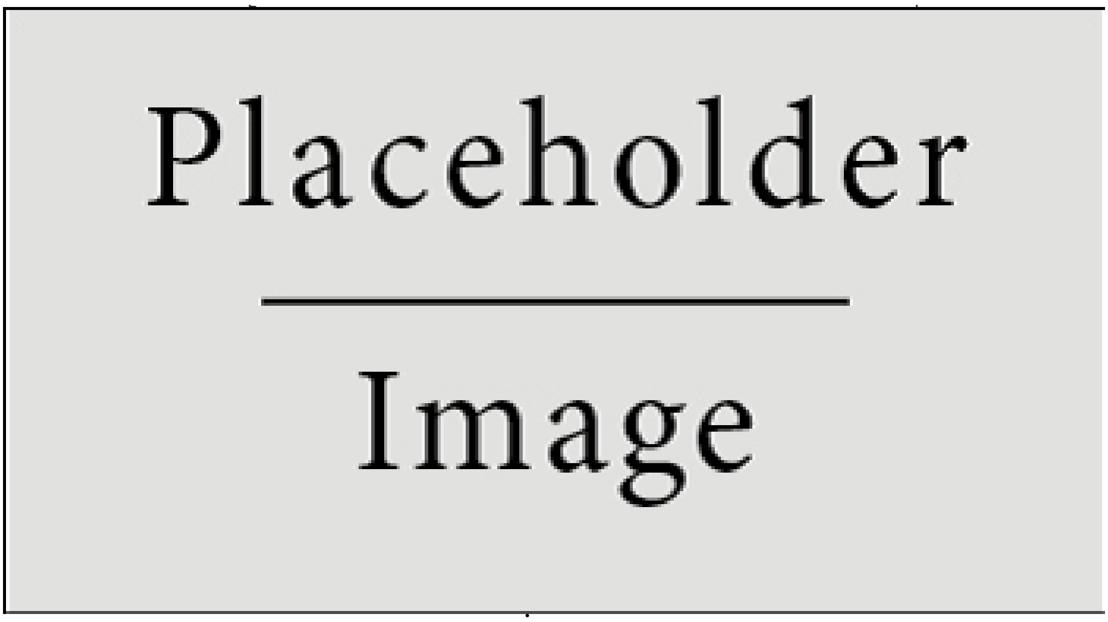



Figure 1.16: Weibull's cumulative distribution function (Source: [3])

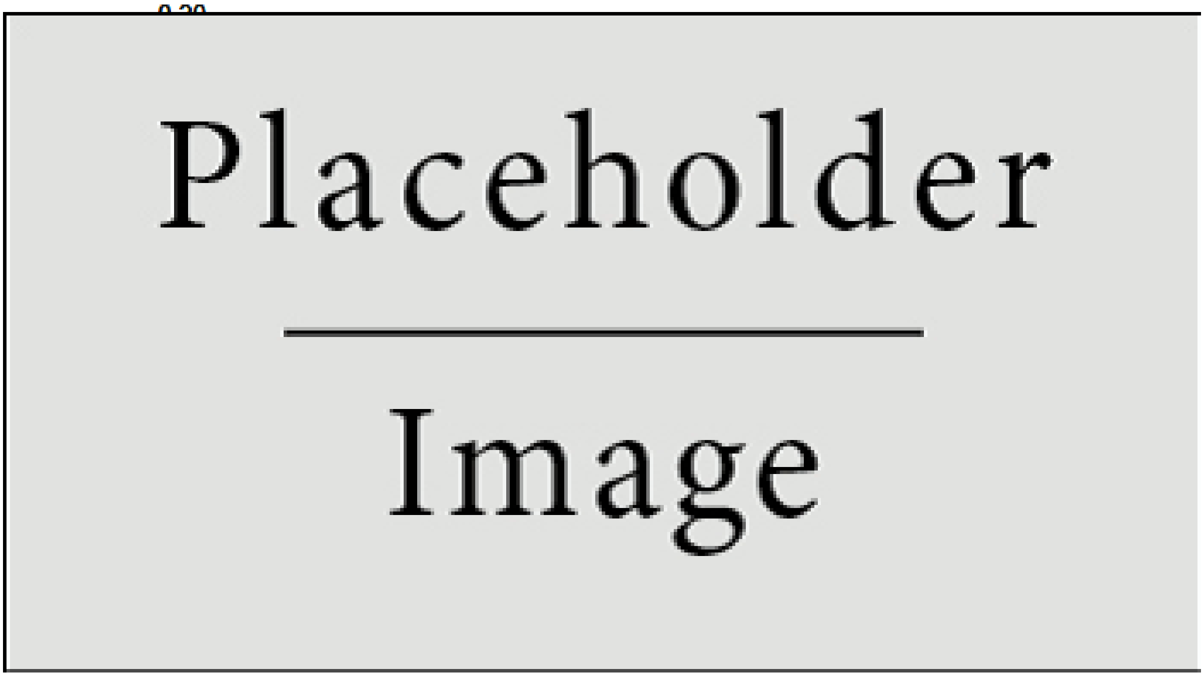



Figure 1.17: Rayleigh distribution curve corresponding to different wind speeds (Source: [2])

the following equation:

$$\bar{U} \approx A \left(0.568 + \frac{0.434}{k}\right)^{1/k} \tag{1.8}$$

In cases where sufficient data is not available, but the mean wind speed of the site is known, the ***Rayleigh*** distribution can be used. For this case the shape parameter is assumed as $k$=2 (Equation 1.9).

$$fd\left(U\right) = \frac{\pi}{2}\left(\frac{U}{\bar{U}^2}\right)\ exp\left(-\left(\frac{\pi}{4}\frac{U}{\bar{U}}\right)^2\right) \tag{1.9}$$

The cumulative distribution according to Rayleigh can be found with Equation 1.10.

$$F(U) = 1 - exp\left(-\left(\frac{\pi}{4}\frac{U}{\bar{U}}\right)^2\right) \tag{1.10}$$

## 1.5 The Annual Energy Production (AEP)

If we count with the frequency density $fd\left(U\right)$ and the power curve of a wind turbine, the Annual Power $APP$ and Energy Production $AEP$ can be estimated using Equations and 1.11, 1.12 respectively [2].

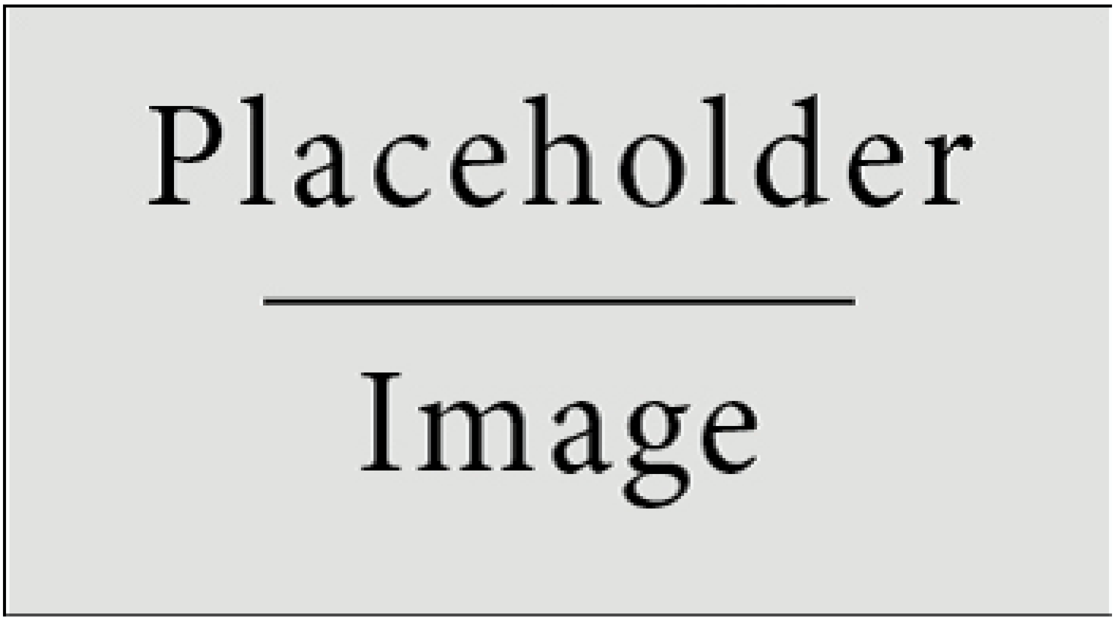



Figure 1.18: Annual Energy Production (AEP) (Source: [2])

$$APP = \sum Fd(U)P(U)\Delta U \tag{1.11}$$

$$AEP = T(APP) \tag{1.12}$$

Figure represents the calculation of the $AEP$. Notice that the power curve was discretized with the same $\Delta U$ used for $fd(U)$. For the calculation, $T$ corresponds to the time interval for which the energy production wants to be calculated e.g. 8760 hours for a year.

## 1.6 Conclusion

How important is to characterize the wind field and do a proper site assessment!, don't you think?. In order to do this throughly, it is necessary to understand, not only the long term wind variations on a specific site, but also how the location's topography can affect the wind resource. The knowledge of the wind field should be completed with the prediction of the vertical wind profile. Only if this is done carefully, a good estimation of the Annual Energy Production (AEP) and a proper feasibility study of the project can be done, since the characterization of the wind field is the foundation for the deign and planning phases of the project.

## 1.7 Literature

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# 3 — Basic Aerodynamic Design

**Learning objectives**

After processing this chapter you will

- Be able to do a basic aerodynamic design of a blade according to blade .
- List the different aerodynamic power losses.
- Describe the causes and consequences of the power losses.

In this chapter you will learn how to do a basic aerodynamic design of a blade of a wind turbine. You will calculate the chord and the twist angle along the blade and you will be able to recognize the parameters playing a role on this dimensioning. The design that you are going to do is based on the ideal case. Therefore, complementarily you will have insights on the aerodynamic power losses that can be generated on the rotor.

Let's do some aerodynamics!.

*Aerodynamic*. Daft Punk
, 2009. URL: `https://www.youtube.com/watch?v=L93-7vRfxNs`.

## 3.1 Optimum blade design according to Betz

In chapter No. 2 we could see that the inflow conditions along the blade change, because the rotational speed $U_{rot}$ is dependent on the radius $r$. Furthermore, we saw in Section 2.6.3 that the aerodynamic forces depend on the geometry of the blade, specifically on the chord and the span. This means that in order to maximize the energy extraction, we could change the blade's geometry along its length to get the best aerodynamic efficiency in each one of its sections.

This is the reason why, Betz proposed to dicretize the rotor into a number of rings (Figure 3.1), so the optimum geometry could be found for each section.

From basic physics it is known that the power produced by bodies in rotational motion depends on the tangential force $F_T$ and the rotational speed $U_{rot}$ [2]. In the case of the wind turbine, since the rotor has an specific number of blades $z$ and each blade section of an specific ring contributes to the power, the total mechanical power produced by each ring can be calculated with Equation 3.1 [3].

$$dP = z\, dF_T\, U_{rot} \tag{3.1}$$

Taking into account that we would like to extract the most energy as we could, the lift should be maximized whereas the drag penalty should remain low. Therefore, we can say that $c_L$ » $c_D$ and we can ignore the drag as a contributor for the tangential force. Replacing the tangential force $F_T$ in Equation 3.1, by the tangential lift component, the power can be redefined as:

$$dP = z\left(\frac{\rho}{2}\, c_L\, (c(r)\, dr)\, U_{rel}^2\, sin\phi\right) U_{rot} \tag{3.2}$$

Where, $c(r)$ and $dr$ are the chord and the span of the blade section.

On the other hand, aerodynamically we can calculate the power as well, rewriting the Equation 2.3, using the area of the ring $A = 2\,\pi\, r\, dr$ and the Betz limit. This will lead to Equation 3.3 [3].

$$dP = \frac{16}{27}\,\frac{\rho}{2}\,(2\pi r dr)\, U_1^3 \tag{3.3}$$

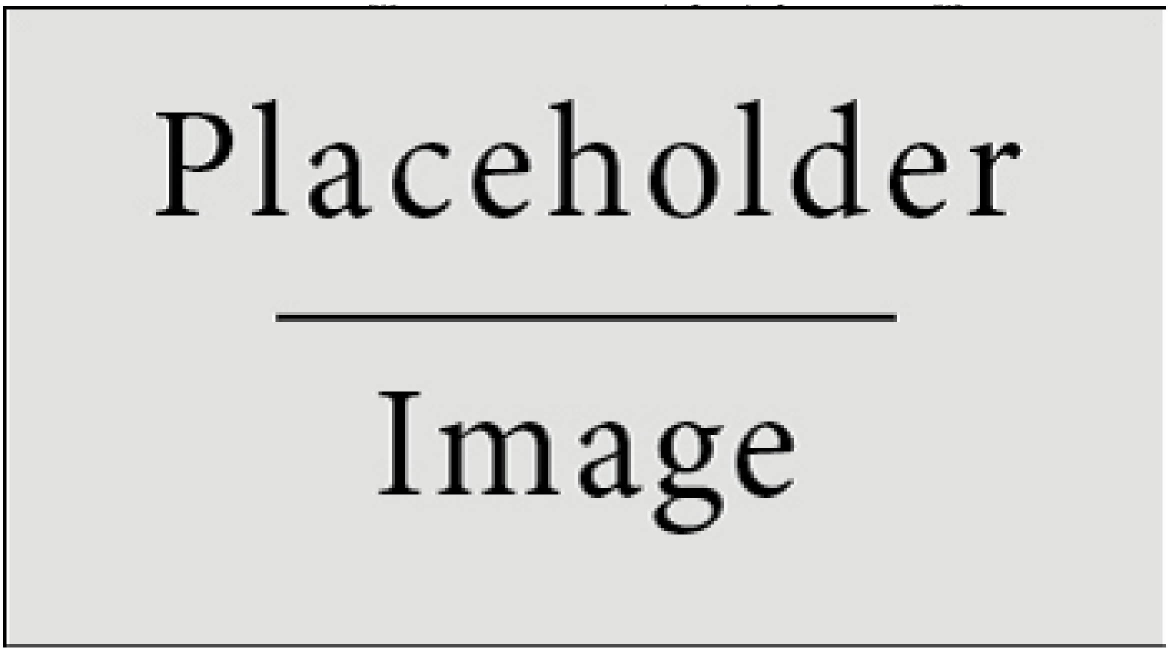


Figure 3.1: Rotor discretization example (Source: [3])

If Equations 3.2 and 3.3 are equated and $c(r)$ is solved, the Equation 3.5 is derived, to calculate the optimum chord.

**Definition 3.1**

**Tip Speed Ratio** $\lambda_D$: is a non-dimensional parameter and corresponds to the ratio between the rotational speed of the wind turbine $U_{rot}$ and the free stream velocity $U_1$. It is used as a baseline parameter to compare the aerodynamic behavior between wind turbines [4].

$$\lambda_D = \frac{U_{rot}}{U_1} = \frac{\Omega R}{U_1} \tag{3.4}$$

Analogously, if $r$ is used instead of $R$ in the previous equation, the local speed ratio corresponding to each blade section can be calculated.

$$c(r) = 2\pi R \frac{8}{9\ z\ c_L} \frac{1}{\lambda_D \sqrt{\frac{4}{9} + \lambda_D^2 \left(\frac{r}{R}\right)^2}} \tag{3.5}$$

**Self-reflection 3.1**


If you are a little bit curious on how to get to Equation 3.5, I encourage you to try to get to it!. It is not straight forward, but I am going to give you a tip: You need Equation 3.4 and the following relations:

$$U_2 = \frac{2}{3} U_1 \tag{3.6}$$

$$U_2 = U_{rel} \sin\phi \tag{3.7}$$

$$U_{rel} = \sqrt{U_2^2 + U_{rot}^2} \tag{3.8}$$

Don't hesitate to ask if you get stuck in any point!

The lift coefficient $c_L$ in Equation 3.5 and the tip speed ratio $\lambda_D$ are the values chosen in the design process. $c_L$ is a value near to the maximum lift to drag ratio $\epsilon$. On the other hand, $\lambda_D$ is generally between 6 and 8, for modern grid connected wind turbines [3].

**Definition 3.2**

**Solidity** $\sigma$: is another non-dimensional parameter representing how much of the swept rotor area is occupied by the blade's area. It can be calculated as follows:

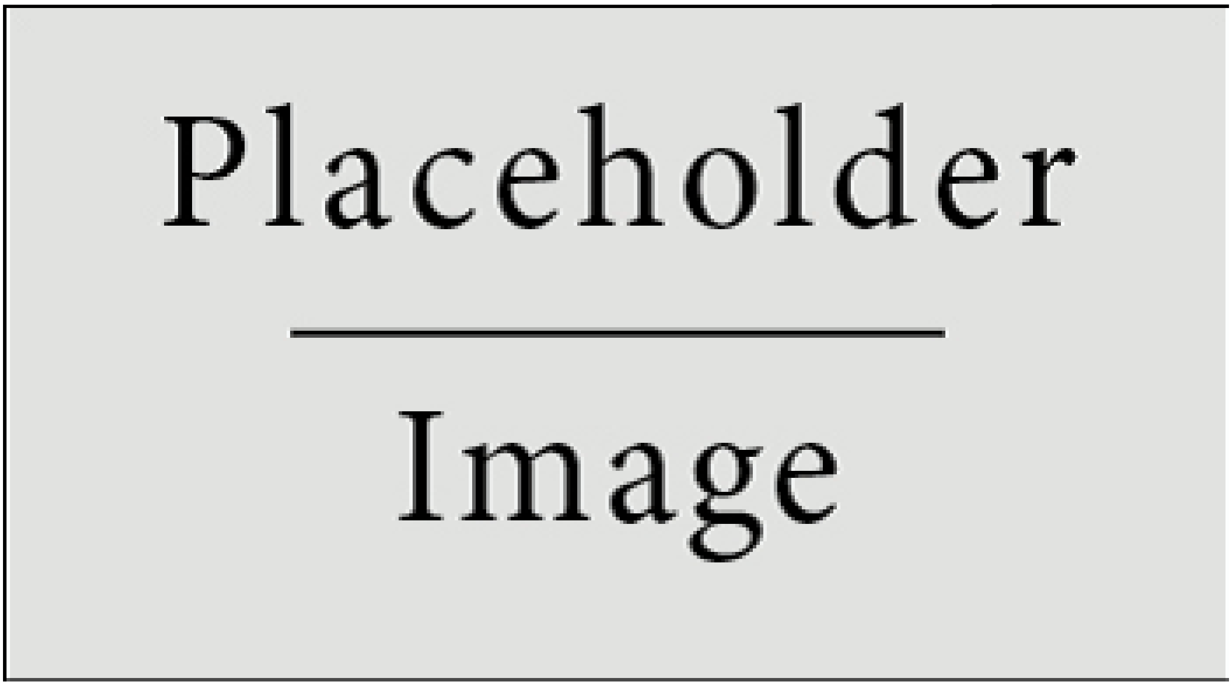


Figure 3.2: Relationship between solidity $\sigma$, design tip speed ratio $\lambda_D$, radius from the blade root to the blade section $r$ and inflow angle $\phi$ (Source: [3])

$$\sigma = \frac{z\,\bar{c}}{\pi R} \tag{3.9}$$

where $\bar{c}$ is the average chord average of a blade.

The solidity is used to compare rotors. In general, a rotor with a high solidity has a large number of blades but low tip speed ratio, whereas a rotor with low solidity moves faster and has a small number of blades.

From Equation 3.5, it can be seen that $c$ is dependent on $\lambda_D$. The higher the $\lambda_D$ the smaller $c$ needs to be. This is also reflected in Figure 3.2, where the relationship between $\lambda_D$, $\phi$, $r$ and $c$ are also exemplified.

Having $\lambda_D$, the inflow angle $\phi$ corresponding to each blade section can be calculated from the velocity triangle (Figure 3.3) with Equation 3.10.

$$\tan\phi = \frac{2\,R}{3\,\lambda_D\,r} \tag{3.10}$$

Subsequently, with the angle of attach $\alpha$ corresponding to design lift coefficient $c_L$, also used for the chord calculation, the twist angle can be found as follows [3]:

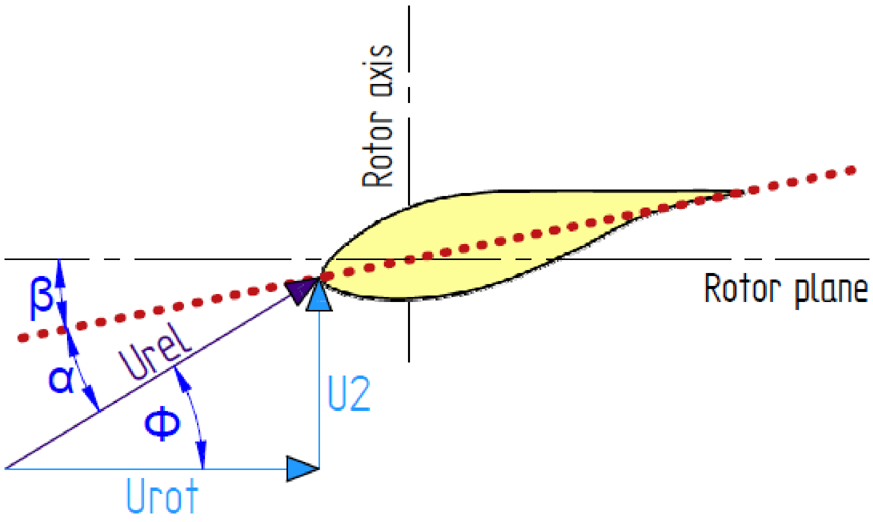


Figure 3.3: Velocity triangle

$$\beta = \phi - \alpha \tag{3.11}$$

Basically $\beta$ is the "physical" angle that we would need to achieve the desired aerodynamic behavior. Specifically, the design $c_L$.

## 3.2 Power losses: Real turbines do not reach Betz limit

As seen in Chapter 2, the Betz limit was obtained with the actuator disc model, which does not account for any losses. Nevertheless, there are three main types of losses that are the reasons why the real turbines do not reach a power coefficient of $c_p$ = 0.59. These are: the profile losses, the tip losses and the wake losses [3].

### 3.2.1 Profile losses

For the ideal blade dimensioning, according to Betz, the drag was neglected in order to come up with Equation 3.2. However drag certainly exist and needs to be accounted for, when the estimated power produced by the turbine is calculated. Equation 3.12 is used to calculate the power at each blade section [3].

$$dP = z \left[ \frac{\rho}{2} \left( c(r)\ dr \right) U_{rel}^2 \left( c_L\ sin\phi - c_D\ cos\phi \right) \right] U_{rot} \tag{3.12}$$

For the purpose of calculating the efficiency of the profile, we would need to calculate the ratio between the power at the rotor blade (Equation 3.12) and the ideal power (Equation 3.2), obtaining Equation 3.13.

$$\frac{dP}{dP_{ideal}} = 1 - \frac{1}{\epsilon\ tan\phi} = 1 - \frac{3\ r\ \lambda_D}{2\ R\ \epsilon} \tag{3.13}$$

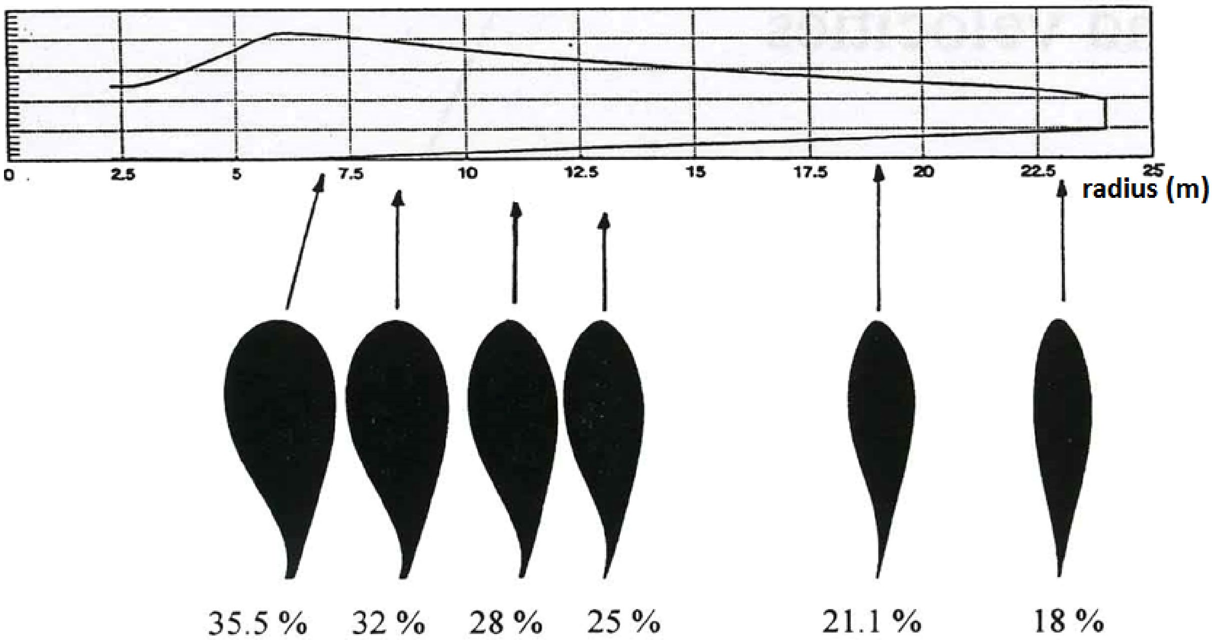


Figure 3.4: Thickness transition of the airfoil along the blade (Source: Modified from IvW TU Delf as cited in [4]).

The highlighted term of the Equation 3.13 correspond to the profile losses, which are proportional to $\lambda_D$ and inversely proportional to $\epsilon$. This means that for a wind turbine with high tip speed ratio ($\lambda_D > 3$), high quality profiles ($\epsilon > 60$) should be used, since the profile losses increase with $\lambda_D$. On the contrary, with low $\lambda_D$, the quality of the profile is not important [3].

Furthermore, from Equation 3.13 it can be inferred that the closer to the tip, the profile losses get higher. Hence, we can conclude that the closer to the tip, the importance of the quality of the profile also increases. The advantage is that thick airfoils can be used closer to the root, to achieve mechanical stiffness and strength [4] (Figure 3.4).

### 3.2.2 Wake losses

As we have seen previously, there is a torque dependent on the tangential force $F_T$ generated on the blade. Due to the action reaction principle, a counteracting torque is also exerted on the air, giving it a rotational movement in the opposite direction of the rotation of the rotor (Figure 3.5). This means that the downstream wind has both a axial velocity component, which we have called $U_3$, and a tangential component. The energy used to give rotation to the air at the rotor is called the wake loss.

On low tip speed ratio $\lambda_D$ wind turbines, normally high torque is acting on the blades. Therefore, high counteracting torque is also produced. On the contrary, for high tip speed ratio $\lambda_D$ wind turbines, the opposite occurs and the wake losses are lower [4].

In Chapter 2, we saw that in Betz theory, only the axial component of the velocity downstream is accounted for when the maximum $c_P$ was found. However, the generation of rotation of the air downstream causes a decrease on the energy extracted. Schmitz included the wake rotation

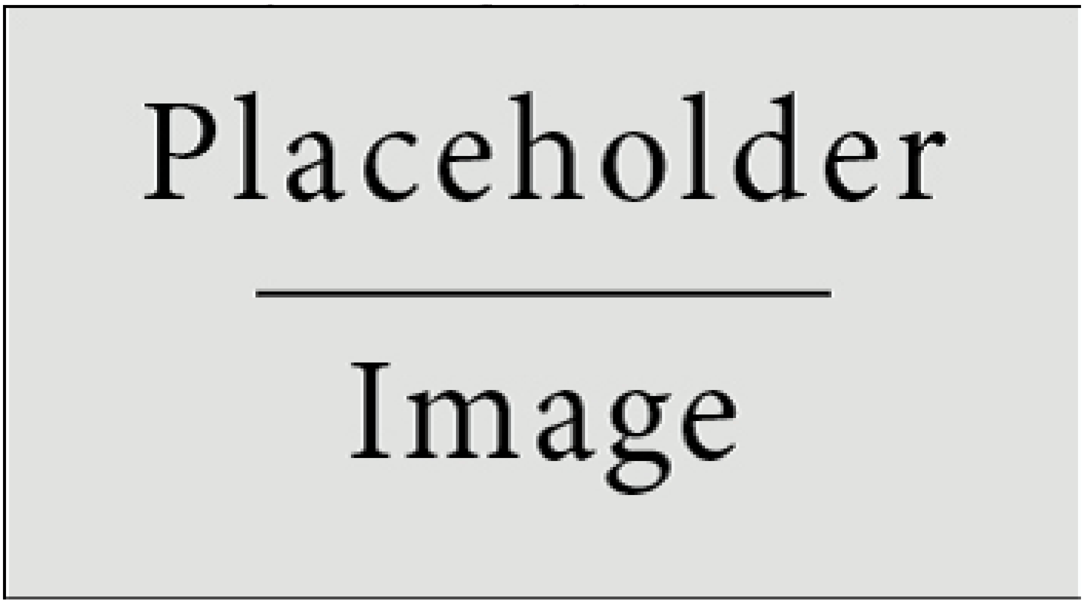


Figure 3.5: Wake rotation (Source: [5]).

in his analysis and found out that the maximum $c_P$ increases with $\lambda_D$, in fact, when $\lambda_D$ is high, a $c_P$ near to the Betz limit can be achieved, as shown in Figure 3.6.

**Definition 3.3**

**Tangential or angular induction factor a':** is a non-dimentional factor that represents the change in tangential velocity experienced by the wind. As soon as the wind leaved the rotor, the tangential rotational speed of the wind $\Omega$ can be expressed as follows:

$$\omega = 2a'\Omega \tag{3.14}$$

In the previous chapter (Section 2.2), we learned that there is also an axial induction factor, with an optimum value of $a$ = 1/3. In Figure, the axial $a$ and tangential $a'$ induction factors, obtained with a turbine with $\lambda_D$ = 7.5, are compared. From the figure, it can be seen that in most of the blade's sections, $a$ is near the ideal value. However, reaching the hub it starts to decrease. On the contrary, $a'$ is not as uniform over the blade as $a$. It starts to increase significantly from the middle of the blade towards the hub [6].

Figure 3.12, further shows the relationship between the lift to drag ratio $\epsilon$, the number of blades $z$ and the maximum power coefficient $c_P$, when the wake losses are taken into account. In general, when the when $\epsilon$ and $z$ decrease, the maximum $c_P$ decreases as well for a certain design tip speed ratio $\lambda_D$ [7].

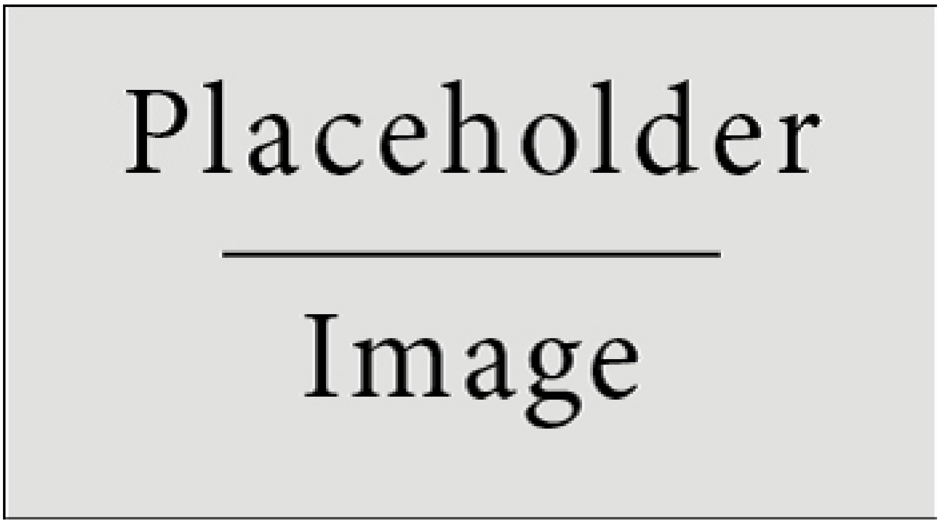


Figure 3.6: Comparison between the power coefficient achieved according to Betz and the one achieved including wake rotation (Source: [6])

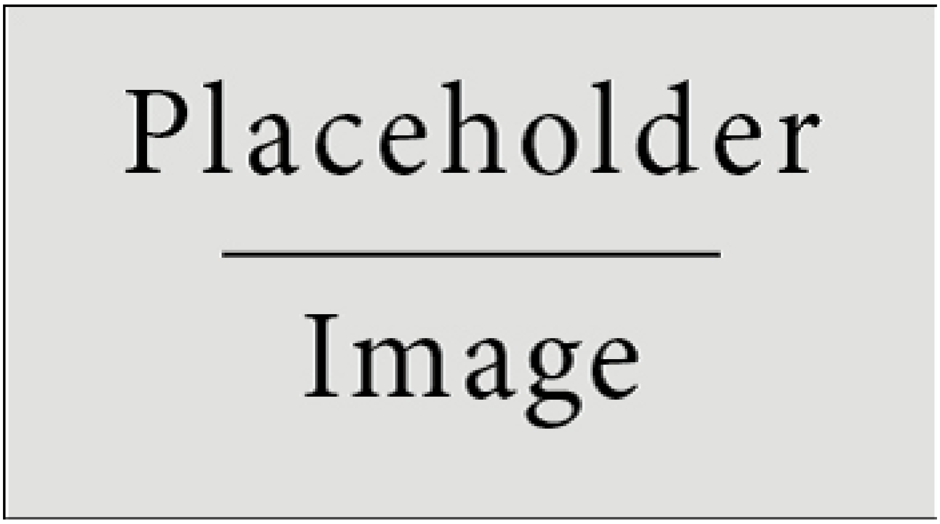


Figure 3.7: Comparison between the axial induction factor $a$ and the tangential induction factor $a'$ (Source: [6])

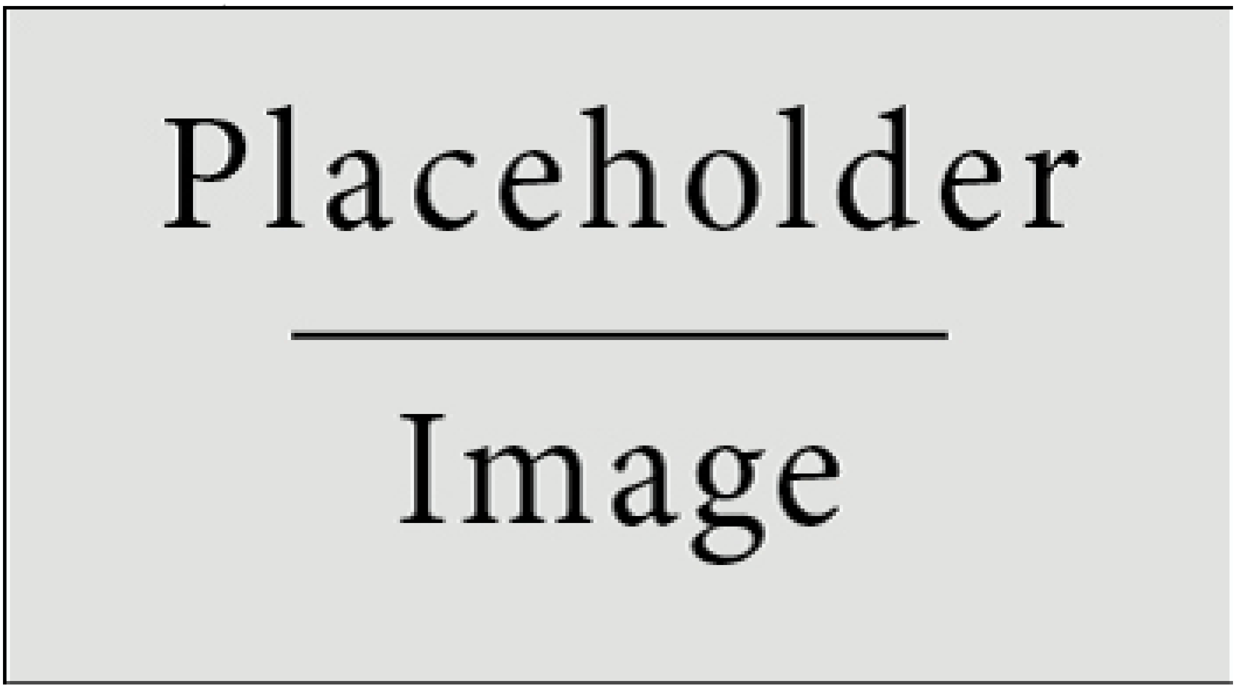


Figure 3.8: Relationship between $c_P$, $\epsilon$ and $z$ (Source: [3])

### 3.2.3 Tip losses

This losses occur due to the flow if air around the tip, from the pressure side to the suction side. This flow creates vorticity around the tip of the blade, that is conserved downwind and expands while it moves aways from the tip (Figure 3.9) [3]. This causes a decrease on lift at the tip.

Figure 3.9 shows that there is a section on the blade where the lift is maintained constant, and another section, reaching the tip, where the lift decreases. Therefore, Betz introduced an effective diameter D', which corresponds to the portion when the lift properties of the blade are conserved, and that is different to the real diameter of the turbine D.

In order to calculate the real diameter, the Equation 3.15 is used. where $b$ is the projection of the arc length between the blades $a$, on a plane perpendicular to the relative velocity $U_{rel}$. This can be seen better in Figure 3.10.

$$D' = D - 0.44b \tag{3.15}$$

In order to put the Equation 3.15 in terms of $\lambda_D$ and $z$, the same relations given in the self reflection 3.1. Then, the result would be:

$$D' = D\left[1 - 0.44\frac{2\pi}{3z}\frac{1}{\sqrt{\frac{4}{9} + \lambda^2}}\right] \tag{3.16}$$

Taking into account that the power is proportional to $D^2$, the tip efficiency can be found with [3]:

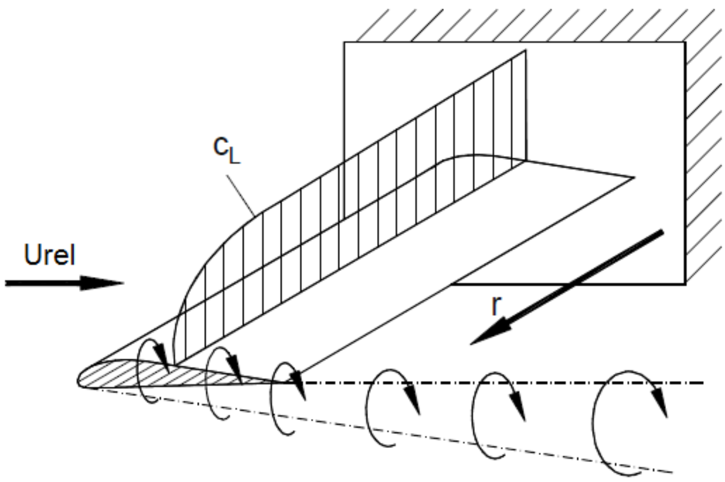


Figure 3.9: Representation of the flow of air around the tip (Source: Modified from [3]).

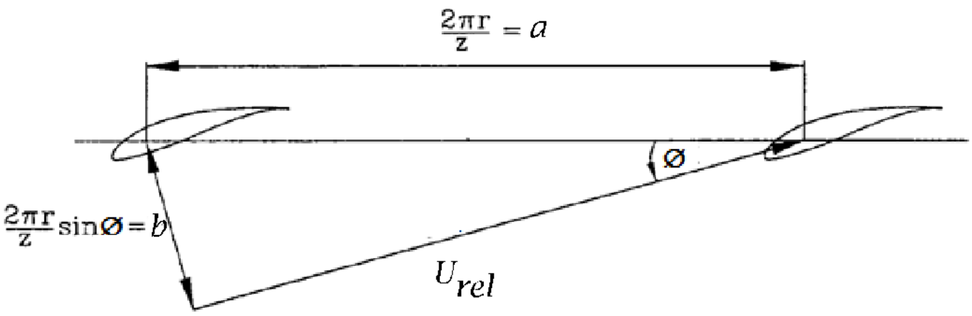


Figure 3.10: Projection $b$ of the arc length between the blades $a$ in a plane perpendicular to $U_{rel}$ (Source: Modified from [4]).

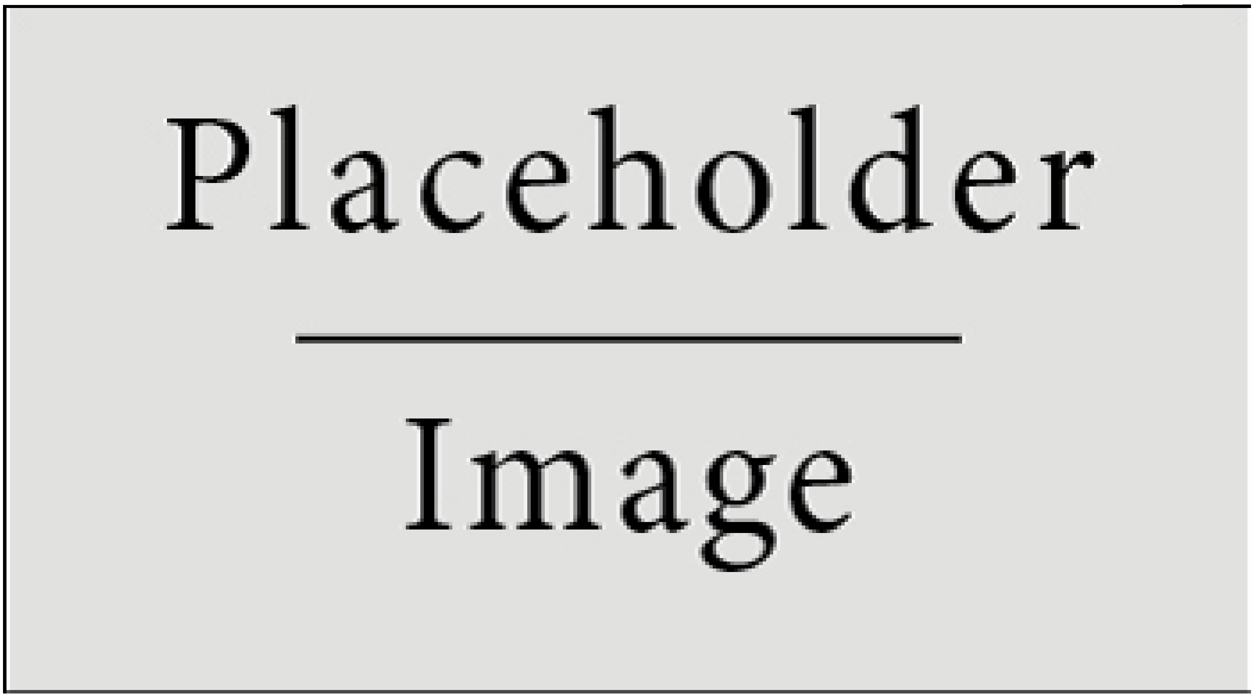


Figure 3.11: Power coefficient dependency on the tip speed ratio (Source: [7])

$$n_{tip} = \frac{P'}{P} = \left(\frac{D'}{D}\right)^2 = \left[1 - \frac{0.92}{z\sqrt{\frac{4}{9} + \lambda^2}}\right]^2 \quad (3.17)$$

If the previous losses are accounted for, it becomes clear than the power coefficient $c_P$ is a function of the tip speed ratio. This is the opposite of the Betz limit, that is a constant value. Figure 3.11, shows how the $c_P$ vs $\lambda$ curve is formed gradually when the losses are taken into account. Please mind that here we are talking about the operation tip speed ratio of a wind turbine $\lambda$ and not the design tip speed ratio $\lambda_D$.

As an example, Figure 3.12 shows the real power coefficient $c_{P-real}$ and momentum or torque coefficient $c_M$ dependent on $\lambda$ of different types of wind energy converters.

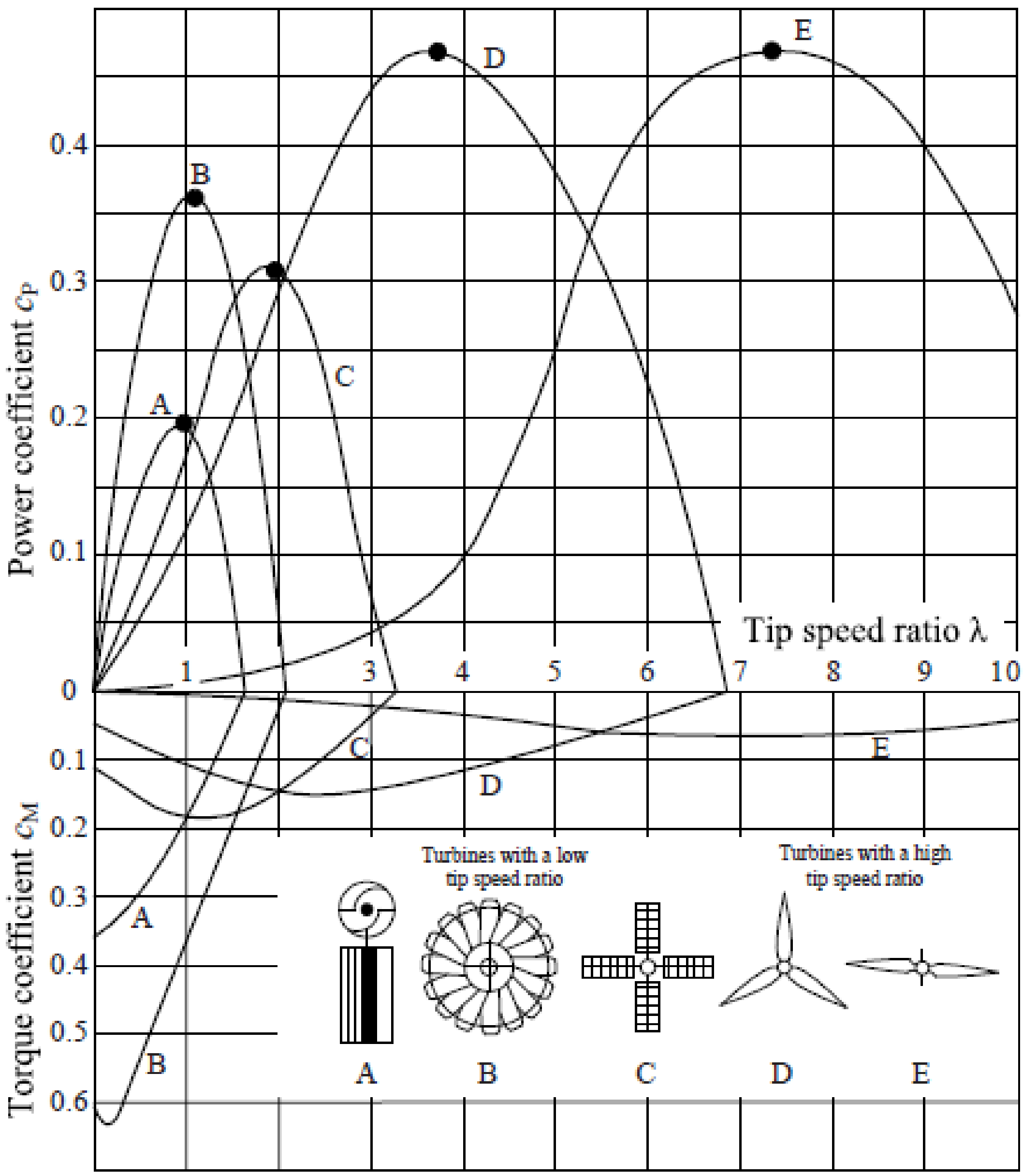


Figure 3.12: Real power and moment coefficients of different types of rotors (Source: [4])

## 3.3 Conclusion

One of the important aspects for you to take home from this chapter is that for different applications there are different wind energy converters. For applications where high torque is required, the low tip speed ratio wind turbines are used e.g. in water pumping or corn mills. On the contrary, when high speed and power is needed, e.g. in electric energy generation applications, the high tip speed ratio wind turbines are used.

Naturally, their constructive features are different. Low tip speed ratio wind turbines have a large number of blades (almost covering all the swept area) and the shape of the blades do not need to have high quality aerodynamic properties. On the contrary, high tip speed ratio wind turbines have fewer and slender blades but their shape and aerodynamic properties are very important to achieve the maximum power extraction.

## 3.4 Literature

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*Speech bubbles*. Designed by winkimages / Freepik, 2017. URL: http://www.freepik.com/winkimages.

# 5 — Wind Turbine Mechanics

**Learning objectives**

After processing this chapter you will

- List and describe the features of the different loads acting on the wind turbine, as well as their sources.
- Establish coordinate systems according with the loads and the component to be studied.
- Explain the response of the wind turbine to effects of the wind field, like gusts and turbulence.
- Compare different eigenmodes of the wind turbine.
- Describe the basis of the scaling procedure of wind turbines.

Basically vibration, fatigue and resonance are the most important words of this chapter:

*"If you want to find the secrets of the universe, think in terms of energy, frequency and vibration."* - Nikola Tesla.

This chapter is mainly focused on giving you insights on the mechanics and dynamics of wind turbines. First of all, we will see the operation nature of this wonderful machines, which have to withstand challenging conditions during their lifetime. Afterwards, you will understand the difference between the types of loads and you will be able to identify their generation sources.

Are there dangerous vibration frequencies? Which are the basis from the scaling process of wind turbines? How different components react to e.g. turbulence and gusts?. These are questions that are going to be answered in this document.

Vibrate along by learning some basis of the mechanics of wind turbines!

*Good Vibrations*. Marky Mark and the Funky Bunch
. URL: `https://www.youtube.com/watch?v=WrG0vp0vjHM`.

## 5.1 The loads acting on wind turbines

From the previous chapters we have seen that wind turbines operate under a stochastic environment and, therefore, they are subject of dynamic loading along all their structure. Besides, since the air has a low density, the machines need to be large to capture a significant amount of energy [2]. However, the larger the turbines are, the more difficult the conditions they need to withstand (e.g. higher wind speeds, uneven loading along the rotor, turbulence, etc.) and higher dynamic loading is going to be produced. Basically, *fatigue* and *resonances* are the situations that need to be avoided.

**Definition 5.1**

**Fatigue:** refers to the progressive damage produced in a material subject to cyclic or random loads, that could lead to failure with lower stresses than the ones occurring with static loading [3].

**Definition 5.2**

**Resonance:** is the response at greater amplitude of a mechanical system, occurring when its vibrations match its natural frequency. The natural frequency is known because it corresponds to the relative maximum amplitude of the system [4].

Normally wind turbines have elastic structures, which is beneficial to reduce fatigue. However, they can be prone to get into resonances easily since the nature of their functioning brings vibrations.

The loads acting on the wind turbines can be classified according with the characteristics of their time series, as follows [5]:

- ***Steady loads:*** are the loads that remain constant over a relative long period. These can occur in static or rotating conditions. For example, a steady wind hitting a wind turbine at stand still, generates static forces on the structure; whereas the same steady wind generates rotating forces (e.g. centrifugal forces) when the system is under rotation (Figure 5.1).

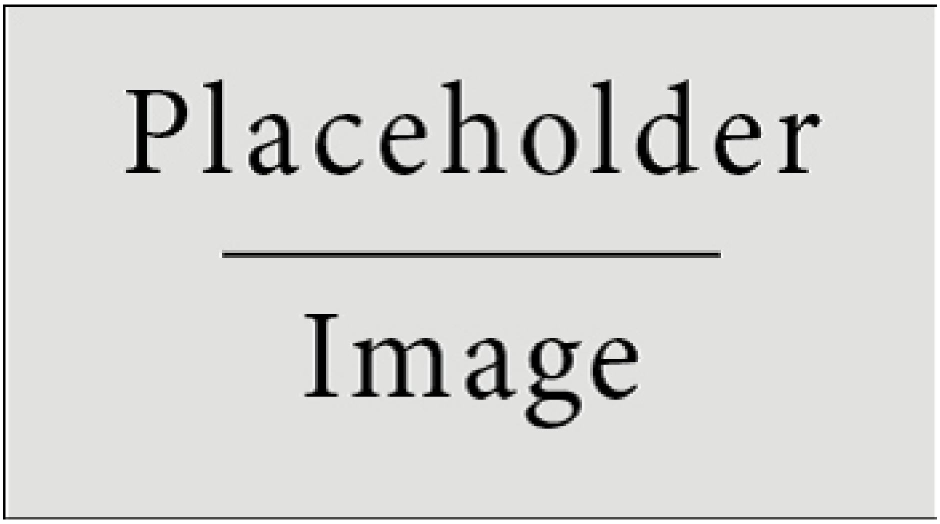



Figure 5.1: Steady load cases (Source [2]).

- ***Cyclic loads:*** these are loads that change in a periodic way and that are governed by the rotation of the rotor.

  Normally, these loads are denoted with the letter $P$ which means $"perrevolution"$. If a load varies periodically 1 time within 1 revolution, then it would be a 1P load. If the load varies 2 or 3 times, the load would be a 2P or a 3P load, respectively. Figure 5.2, shows the impulse acting on the tower-nacelle when the blade passes in front of the tower. Since the wind turbine has 3 blades, 3 impulses will be given to the tower-nacelle "per revolution". This is evident in the plot $thrust$ vs. $rotationalangle$ (Figure 5.3).

- ***Transient:*** are the loads that occur due to a short duration event e.g. wind gusts. Even though these loads are only temporary, their magnitude could be considerable.

- ***Stochastic:*** correspond to the loads that have a random behavior. The clearest examples are the loads generated due to turbulence in the wind (Figure 5.4b).

Complementarily, the sources of loading are listed below [7]. In Table 5.1, the sources of loading and the types of loads are related.

- ***Aerodynamics:*** the forces generated due to the interaction between the wind and the blade, e.g. the lift and drag forces.

- ***Gravitation:*** the self-weight of the blades.

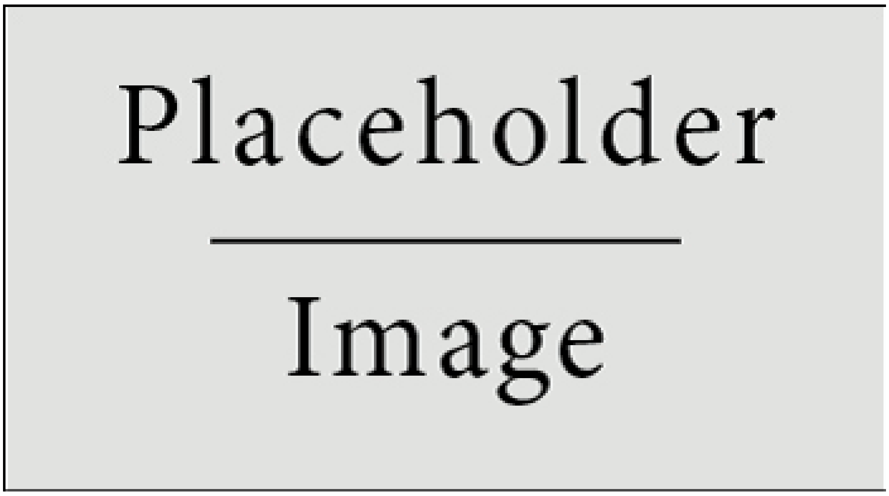



Figure 5.2: Effect on the thrust in the tower of a 3 bladed wind turbine (Source: [6]).

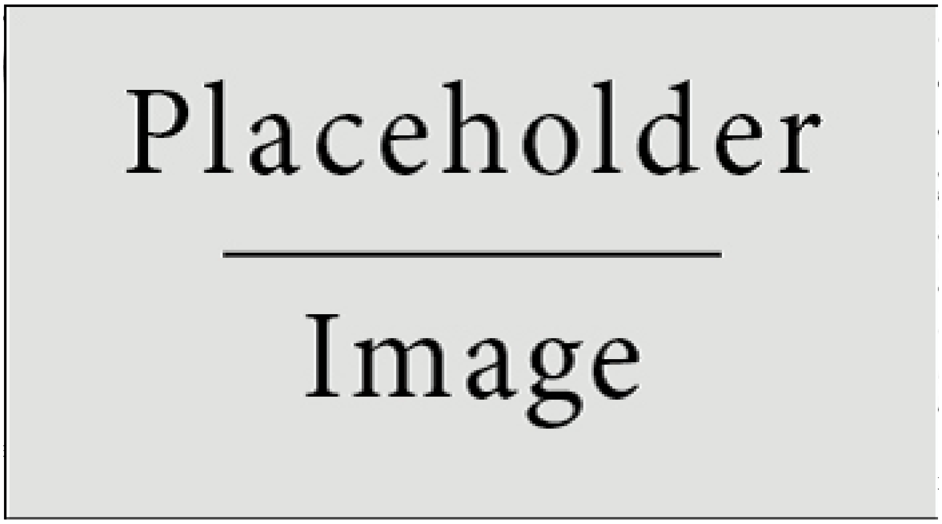



Figure 5.3: Cyclic load cases (Source [2]).

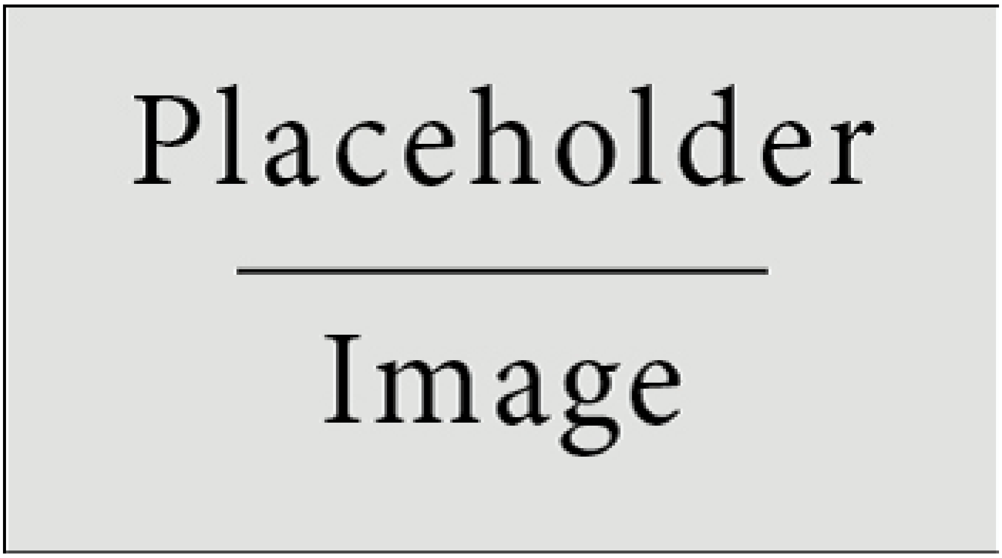



Figure 5.4: Loads examples (Source [2]).

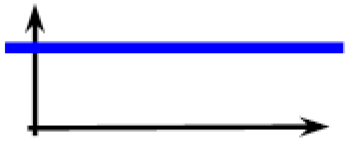
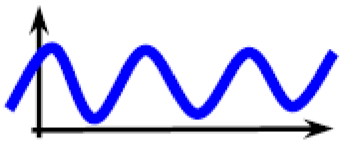
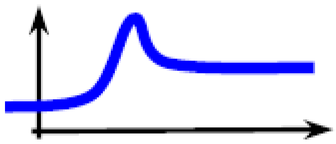
| Types of loads | Loads | External event | Operation |
|---|---|---|---|
|  (a) Steady (Source: [6]). | Gravity force<br>Centrifugal force<br>Mean Thrust | Weight<br>Rotation<br>Mean wind speed | Normal operation |
|  (b) Periodic (Source: [6]). | Mass unbalance<br>Aerodynamic forces | Unbalance<br>Tower shadow<br>Oblique flow<br>Blade passage | Normal operation |
|  (c) Stochastic (Source: [6]). | Aerodynamic and hydrodynamic forces | Turbulence<br>Earthquake<br>Wakes or rain | Normal operation |
|  (d) Transient (Source: [6]). | Frictional forces<br>Aerodynamic forces<br>Braking forces | Shut down of the system<br>yawing | Manoeuvre<br>Malfunction<br>Extreme conditions |

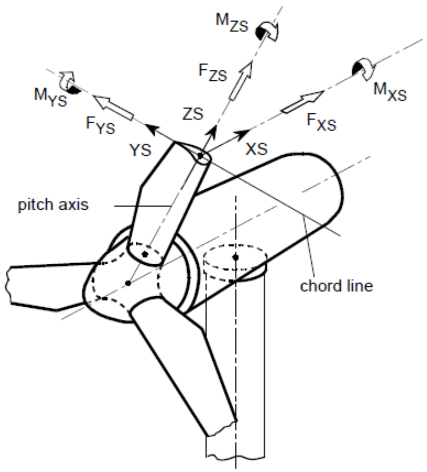
Table 5.1: Types of loads and loads sources (Source: [6]

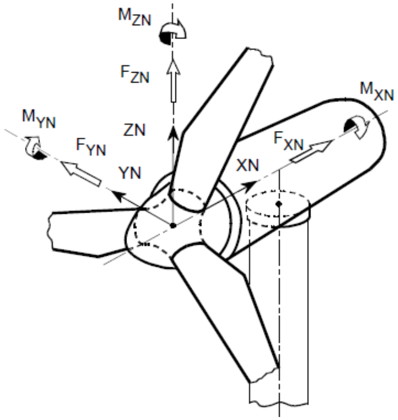
- ***Inertia:*** the centrifugal force acting on the blades under rotation and the gyroscopic load generated when the rotor is yawed into the wind (Figure 5.4a) [2].
- ***Operation:*** the forces generated due to the normal operation of the turbine e.g. blade pitch and braking the rotor; and due to failure e.g sudden disconnection from the grid.

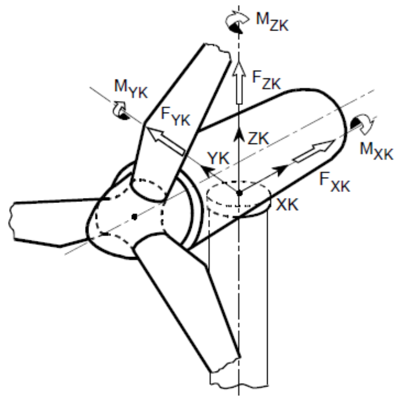
## 5.2 Coordinate system and terminology

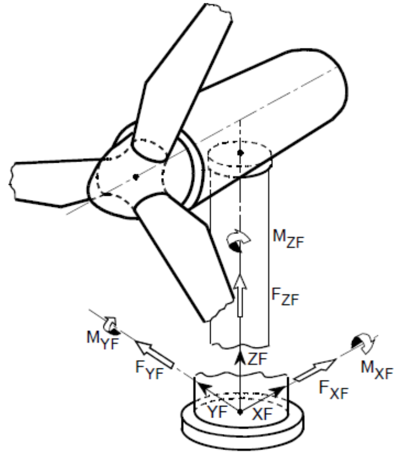
We can say that a wind turbine has two wide types of coordinate systems: *rotating* and *fixed*. Normally, for the mechanical design, a coordinate system is assigned to each component of the wind turbine, depending on its operation nature. For example, a blade, which is a rotating component, can have both, a rotating and a fixed system [2].

There is no fixed standard for the coordinate system. Therefore, it is task of the designers to decide the coordinate systems to be used for an specific project. In Table 5.2, four exemplary coordinate systems are shown for four different components of the wind turbine.

<table>
<tr><th colspan="4">Examples of coordinate systems for the blade, the hub, the nacelle and the tower of a wind turbine</th></tr>
<tr>
<td>

(a) Blade rotational coordinated system (Source: [8] ).</td>
<td>

(b) Hub fixed coordinated system (Source: [8] ).</td>
<td>

(c) Nacelle rotational coordinated system (Source: [8] ).</td>
<td>

(d) Tower base fixed coordinated system (Source: [8] ).</td>
</tr>
<tr>
<td>The origin of the blade coordinate system is placed in the intersection of the pitch axis of the blade and the chord line of the airfoil. It rotates with the rotor and along the pitch axis.</td>
<td>The origin is placed at the rotor center and it is fixed. It does not rotates with the rotor.</td>
<td>Its origin can be placed either in the intersection of the rotor axis and the tower axis or in the point where the nacelle interconnects with the tower along the tower axis. It rotates according with the yaw angle.</td>
<td>It is placed in the tower base, along the tower axis and it is a fixed system.</td>
</tr>
</table>

Table 5.2: Coordinate systems for different wind turbine components (Source: [8] [9]

We are going to come back now to the blade example and take the rotating system shown in Figure 5.3a. Generally in the wind energy field there are two important terms used for the blade forces: *flapwise* and *edgewise*.

***flapwise*** refers to the forces and moments acting on the blade that make it to bend in the direction perpendicular to its chord line. In relation to the coordinate system shown in Figure 5.3a, the flapwise force would be $F_{xs}$ and the flapwise bending moment corresponds to $M_{ys}$.

Complementary the forces acting on the blade that make it to bend parallel to the chord line are called ***edgewise***. In Figure 5.3a, $F_{ys}$ and $M_{xs}$ for the edgewise force and the edgewise bending moment, respectively. Figures 5.5 and 5.6 show the flapwise and edgewise deflection of a blade.

Additionally, the blades can have a fixed coordinating system, like the one in Figure 5.3b for the hub, to identify forces like the thrust, perpendicular to the rotor plane, and the tangential force, parallel to the rotor plane, like shown in Figure 5.7.

**Self-reflection 5.1**


A very interesting aspect related with the mechanical design of wind turbines, is that a force acting on one component could be perceived differently by another component. I would like to give you one example:

A blade unbalance is perceived by a blade as an axial stationary force. when this force is transfered to the nacelle, it is felt by it as cyclic load with $1P$ excitation. This, taking into account that the force comes from the rotating rotor (Figure 5.8).

A similar case occurs with the gravity. From the perspective of a fixed coordinate system of a fixed component e.g. the nacelle, the weight of the blade will act always with the same magnitude and the same directions. However, the blade under rotation perceives the gravity in a different way, since the its direction changes respect to its rotating coordinate system (Figure 5.9.

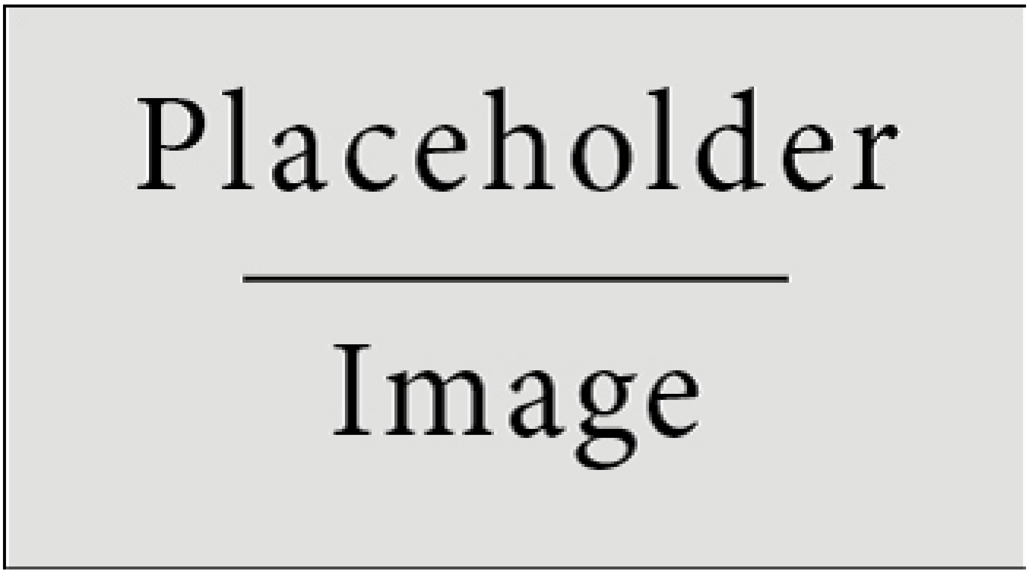



Figure 5.5: Flapwise deflection of the blade (Source: [10]).

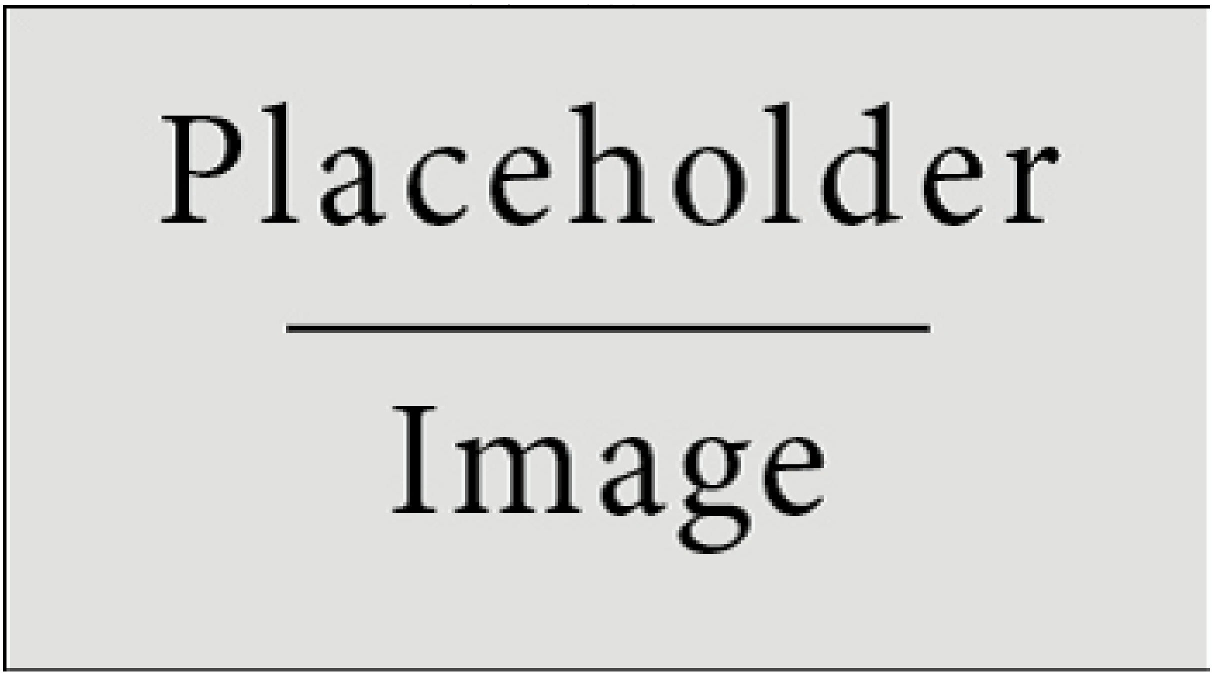



Figure 5.6: Edgewise deflection of the blade (Source: [10]).

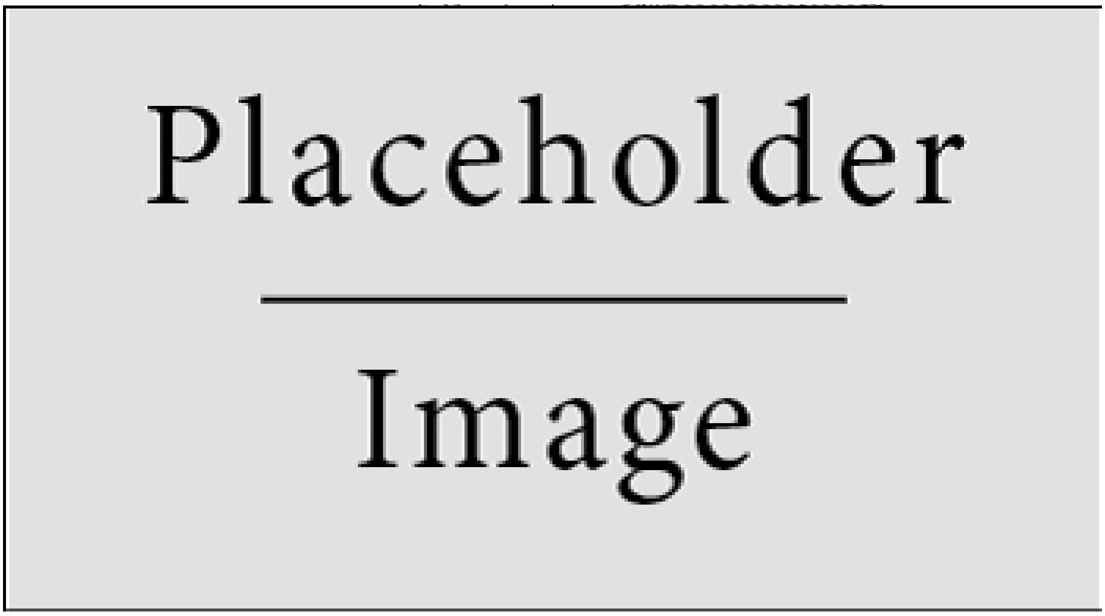



Figure 5.7: Loads on the rotor (Source: [2]).

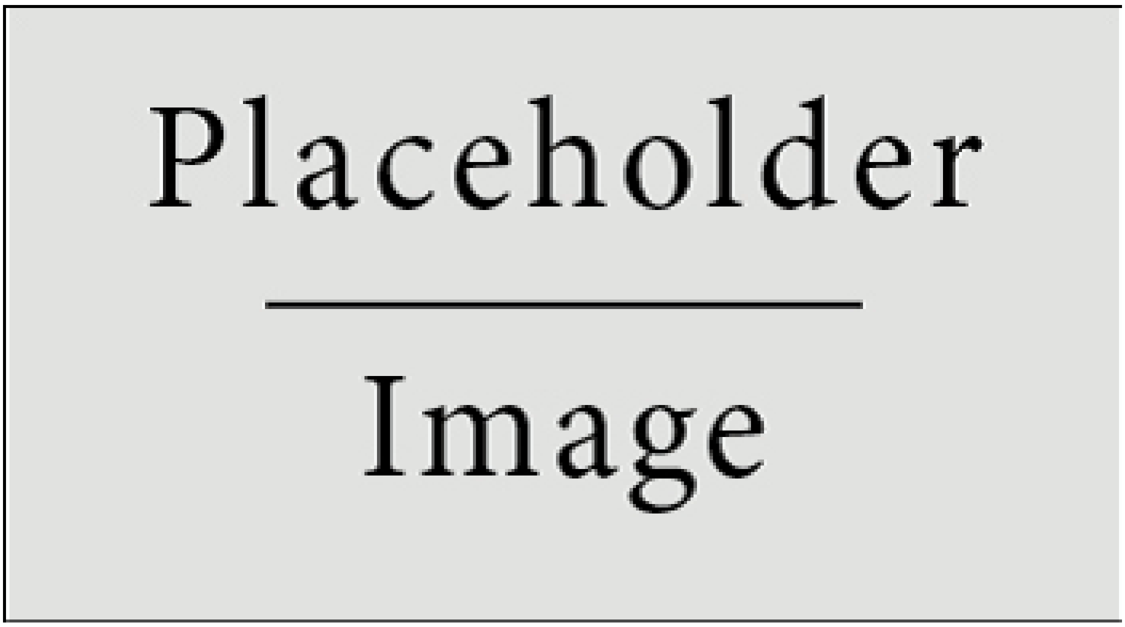



Figure 5.8: Unbalance (Source: [2]).

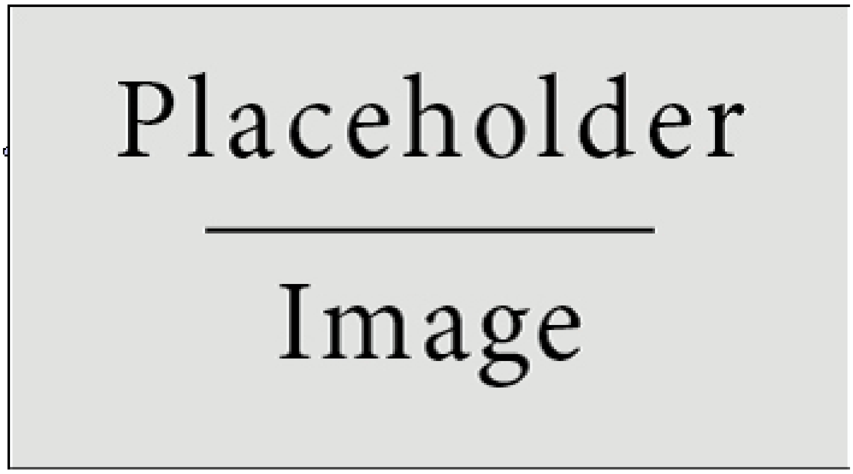



Figure 5.9: Gravity (Source: [2]).

## 5.3 Effect of turbulence and partial gusts

The stochastic nature of the wind is the reason why wind turbines operate under a very dynamic loading. During the mechanical design of a wind turbine, the fluctuations around the short-duration mean need to be accounted for, since they contribute either to the fatigue of the materials or to the generation of extreme loading. These fluctuations can get to a point where fracture can occur [7] [2].

Besides this, Gusts also play a big role in the loading of large wind turbines. They are short-term duration and spatially limited phenomena. They can last from 3 to 20 seconds and measure from 10 to 100 radially, when taking the swept area of the wind turbine as reference [6].

According to these features, normally the gust hits partially the rotor's area. Additionally, its duration time can be enough for each rotor blade to pass a plurality of times through the gust's structure. This situation generates and harmonic loading of the blade with excitations of 1P, 3P, 6P, etc. Having in mind that the blades "cut" the gust, the name given to this is *eddy slicing* or *rotational sampling*.

The rotational sampling is represented in Figure 5.10. It can be seen that the response is different at the hub and in different places of the blade. Since the hub is fixed (point 1), the response is constant taking into account that it is always under the effect of the gust in its entire duration. On the contrary, point 2 and point 3 show a 1P response. The difference between these two points lies on the time that each section of the blade stays in the gust structure.

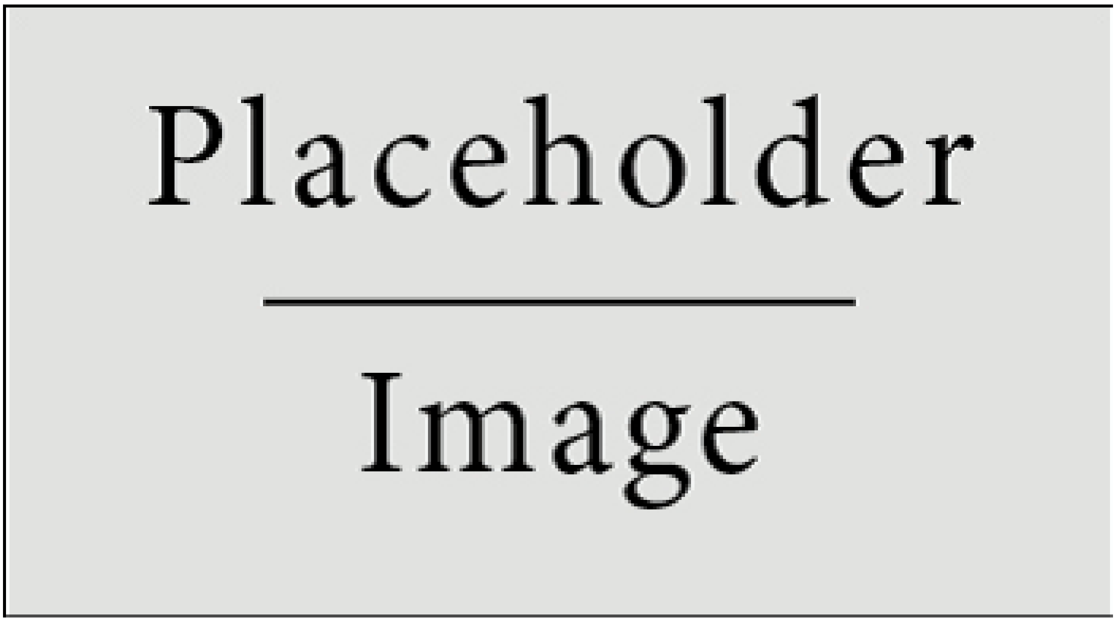



Figure 5.10: Representation of rotational sampling (Source: [6]).

## 5.4 Overall system vibrations

The dynamics of the whole turbine is a very interesting topic. We could think that each component of the turbine can be separately designed. However, when a component is vibrating, what happens with the components joined to it?...

A wind turbine is a "fatigue machine" and it is advisable to study it in sets of components, depending on their interaction with each other, for example [6]:

- the blades, the rotor and nacelle system.
- the drive train system (Generator and gearbox).
- the main components of the turbine (rotor, nacelle, drive train and tower).

Even though each component alone has its own natural frequency, it can belong to a sub-system with a totally different natural frequency. This occurs, for example, in large wind turbines, where the blade's edgewise natural frequency is within the range of the torsional natural frequency of the drive train. This means that the whole system, from the blade to the drive train, is dynamically coupled and should be studied as a set of components that work together rather than as individual components [6].

Likewise, the sub-systems' natural frequencies affect the whole wind turbine. This way the *mode shapes* or *eigenmodes* are created. Table 5.3 shows the different mode shapes of a simplified system composed with the rotor, the nacelle and the drive train (Figure 5.11).

**Definition 5.3**

***Mode shape:*** is the movement pattern followed by a vibrating system when a specific frequency is reached.

The mode shapes are found through simulation models. The designers choose the degrees of

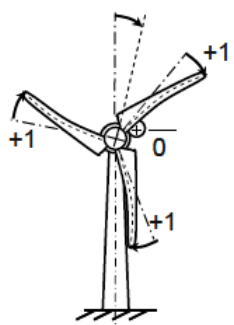
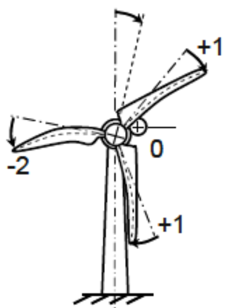
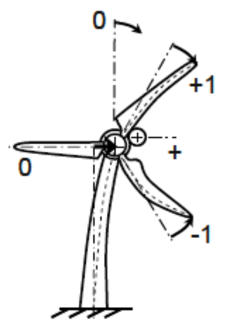
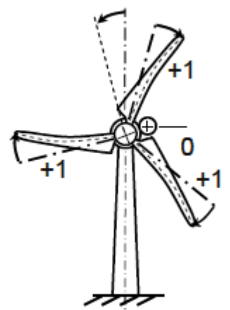
| Examples of the mode shapes for the wind turbine | | | |
|---|---|---|---|
|   (a) Mode 1 (Source: [6] ). |   (b) Mode 2 (Source: [6] ). |   (c) Mode 3 (Source: [6] ). |   (d) Mode 4 (Source: [6] ). |
| The blades and hub oscillate towards the generator. | Two blades are oscillating and the third blade acts as a balance osculating with two times the amplitude of the other two. Due to the shape of this mode, it is is called $\lambda$-shape. The moments at the hub are balanced. | Two blades are oscillating in opposite directions, while the third one has no vibration. This is called the $Y$ eigenmode. Here the tower moves with the other components of the system and the moments at the hub are balanced. | The oscillation of the blades is similar to the eigenmode 1, however, here there is oscillation of the hub in opposition to the movement of the blades. |

Table 5.3: Coordinate systems for the nacelle and the tower base (Source: [6] [9]

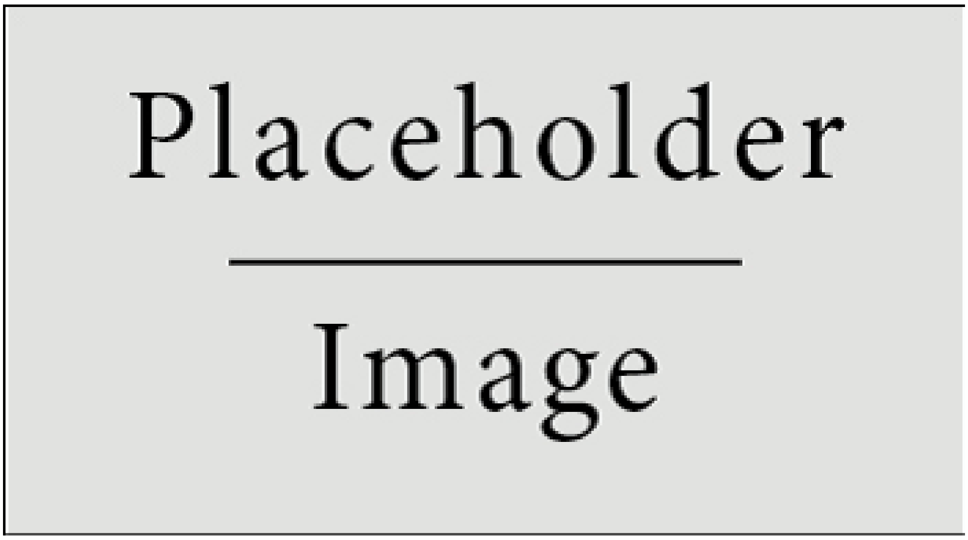



Figure 5.11: Simplified drive train system (Source: [6]).

freedom of the components and sub-systems, in order to come up with their natural frequency. For example, the blades can be defined as rigid structures, to study the dynamic coupling between the nacelle and the tower. In relation with the example of Table 5.3, the blades are defined as elastic components.

In this link you will find 26 mode shapes of a wind turbine modeled in the software ASHES. Check it out!: https://www.youtube.com/watch?v=Uv-AdNAm7WM.

## 5.5 Scaling of wind turbines

It is clear now that the current trend for wind turbines is to increase in size. This is difficult since the process of scaling goes to sizes never experienced and, therefore, there can be a significant level of uncertainty during the scaling process. The advantage nowadays lies on the research carried out in the physics around the operation of wind turbines, as well as in their aerodynamic and mechanical design. This can serve as a baseline for making better predictions and maybe reduce the uncertainty regarding the aerodynamic and mechanical behavior of the new machine.

From the chapter 4, we have seen that the $c_P$, $c_M$ and $c_T$ characteristics can describe the aerodynamic behavior of a wind turbine under different operating conditions. Additionally, they can also describe the behavior of wind turbines of different sizes [6]. In fact, the term "scaling" means that both, the reference object and the object with the new size, have similar features in their geometry, kinematics and dynamics. This is also called the *theory of similarity*, where basically the difference between the objects is their size [11].

For the case of a wind turbine, in oder to accomplish similarity, the following conditions should be met [6]:

- The tip speed ratio $\lambda$ should be maintain. If the radius of the turbine $R$ increases, then the rotational speed $\Omega$ should decrease in the same proportion. This would lead to the conser-

| **Parameter** | **Relative** | **Proportional** |
|---|---|---|
| Power | $P_2/P_1 = R_2/R_1$ | $\approx R^2$ |
| Torque | $M_2/M_1 = R_2^3/R_1^3$ | $\approx R^3$ |
| Thrust | $T_2/T_1 = R_2^2/R_1^2$ | $\approx R^2$ |
| Angular speed | $\Omega_1/\Omega_2 = R_2/R_1$ | $\approx R^{-1}$ |
| Weight | $W_2/W_1 = R_2^3/R_1^3$ | $\approx R^3$ |
| Aerodynamic and centrifugal forces | $F_2/F_1 = R_2^2/R_1^2$ | $\approx R^2$ |
| **Stresses due to** | **Relative** | **Proportional** |
| Weight | $\sigma_{W2}/\sigma_{W1} = R_2/R_1$ | $\approx R^1$ |
| Centrifugal and aerodynamic forces | $\sigma_{F2}/\sigma_{F1} = 1$ | $\approx R^0$ |

Table 5.4: Scaling rules for the wind turbine (Source: [6])

vation of the inflow conditions, as shown in Figure 5.12.

- Proportional adjustments to the dimensions should be done e.g. to the radius and chord length.

- Keep the airfoil, materials and number of blades unchanged.

The theory of similarity bring the fundamental understanding for the scaling process of wind turbines, but has its own limitations that need to be accounted for, during the detailed design process. Sometimes, the *similitudes* can be broken because, for example [11]:

- larger wind turbines can often experience higher wind shear along their rotor than the reference wind turbine.

- Size effects related with the mechanical behavior of the machine: fracture mechanics of the materials, risk of failure due to weight induced loads, buckling and larger deflections.

- Change in the Reynolds number and boundary layer. The Reynolds number for the reference turbine can be already large, therefore, this effect is often insignificant.

The results obtained from the application the theory are the scaling (proportionality) rules of different design parameters, forces and stresses. Examples of these rules for wind turbines are shown in Table 5.4.

Normally, the radius $R$ or the diameter $D$ is the baseline dimension used to apply the theory in wind turbines. The rules can be expressed with the form $aD^n$. The exponent $n$ is determined by physic and engineering considerations, whereas $a$ is defined based on the manufacturing processes, materials or any other aspect involved in the wind energy technology learning curve [11].

If you are curious on how these rules are developed, yo can go to the references: [6] [11] [12].

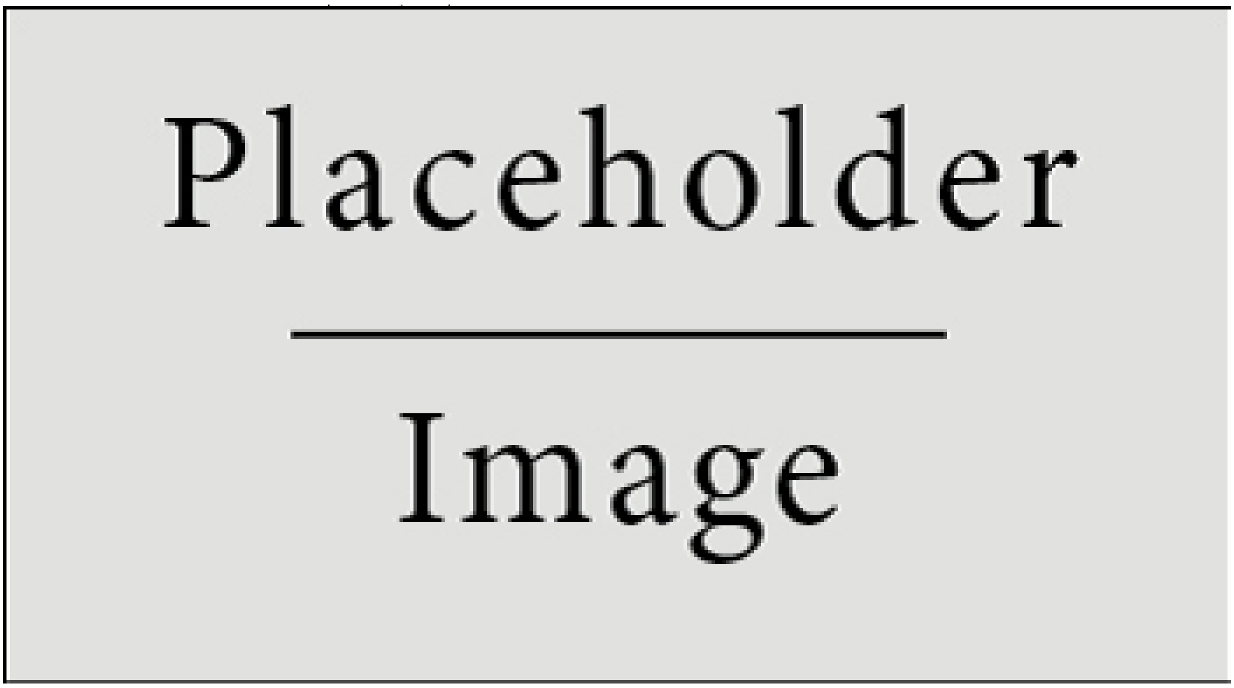



Figure 5.12: Inflow conditions for scaled wind turbine (Source: Modified from [6]).

## 5.6 Conclusion

When one sees a wind turbine for the first time, is hard to imagine the degree of complexity that these machines have behind their planning, design and operation. Besides thinking on extracting the energy in the most efficient way, the turbine must survive to the stochastic nature of the wind field.

If the structural safety would be the issue only, the solution would be easy. The more robust is the wind turbine, the less is the risk of failure. However, as we have seen in the scaling rules, weight increases with the cubic of the radius. This means that the more robust the design, the cost of the turbine increases exponentially as well.

Fortunately, the turbine should be aerodynamically efficient, strong and cost effective. During the history of wind turbines, these challenges have been solved. With the increasing size, more challenges are yet to come. All of this make this machines fascinating.

## 5.7 Literature

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