TECHNICAL UNIVERSITY OF CRETE

School of Production Engineering & Management

M.Sc. THESIS

Wind Turbine Airfoils

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A dissertation submitted in partial fulfillment of the requirements for the Master's degree (M.Sc.)

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Acknowledgements

I would like to dedicate this work to my husband for his continuous support (and all the burnt foods) and to my daughter Vasilia. Also, I would like to thank my supervisor Professor I. K. Nikolos, for his support throughout the completion of this work.

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Abstract

This MSc Thesis, conducted at the School of Production Engineering & Management, Technical University of Crete, deals with the airfoils used for the design and construction of wind turbine blades. The Thesis consists of three chapters.

The first chapter is an introduction and a background section, concerning the necessity of renewables in the future of energy production, worldwide. The second chapter describes the various categories of wind turbines that are used today for energy production. The third chapter is the main chapter of this Thesis and contains the various airfoil families that have been developed in the last decades especially for the design and construction of wind turbine blades. Moreover, the specific characteristics of such airfoils are discussed.

Abbreviations

GHG Greenhouse Gas

NGO Non-Governmental Organization

IT Information Technology

DER Distributed Energy Resources

HAWT Horizontal Axis Wind Turbine

VAWT Vertical Axis Wind Turbine

AoA Angle of Attack

NACA National Advisory Committee for Aeronautics

Contents

1. Introduction

The anthropocentric way of living is the main reason of the climate change problem. The greenhouse gas (GHG) emissions (Figure 1.1) have been radically increased, during the last decades and especially in the 90s. As the people buy more consumables and wish to have a more luxury and easy way of living, a constant increase in the industry production is required, requiring more fuels and producing more gases.

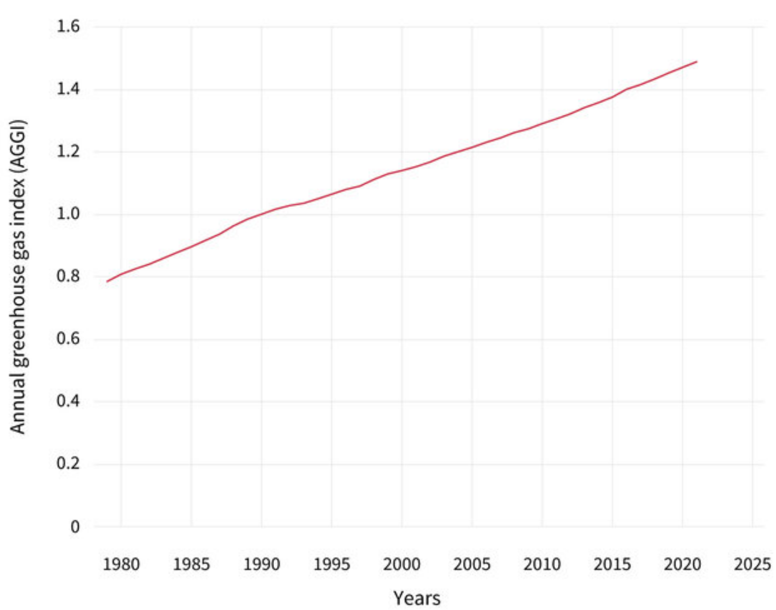


Figure 1.1 The AGGI (Annual Greenhouse Gas Index) reports the combined warming influence of the long-lived greenhouse gases as a fraction of their influence in 1990. NOAA climate graph based on data from NOAA Global Monitoring Lab.

Climate change has affected all the regions around the world. The undesirable impacts are and will be tremendous and cost much more than preventing it. The recent IPCC Special Report on Global Warming has emphasized the urgency of taking significant steps. The transformation of global energy use can be a way of reducing the environmental problems. Considering the two thirds of GHG emissions originate from the energy sector, a great shift towards renewable energy and energy efficiency can be the solution (IPCC, 2018) [International Renewable Energy Agency, 2019] (Figure 1.2).

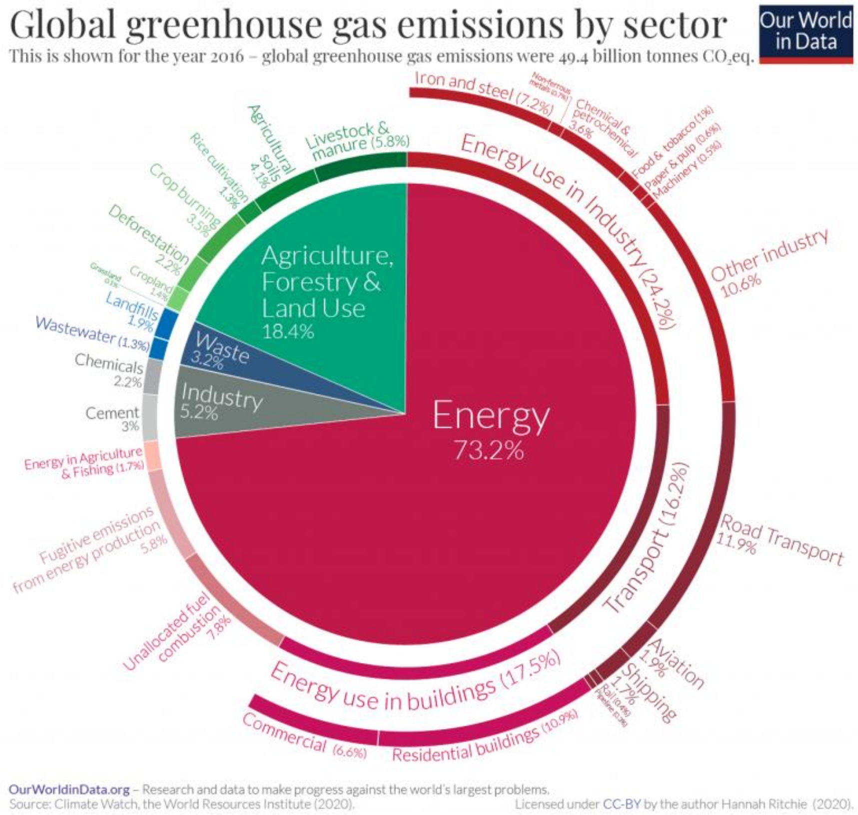


Figure 1.2 Global greenhouse gas emissions by sector (year 2016).

Further than governmental actions for preventing further climate change, communities and non-governmental organizations (NGOs) have combined their knowledge in order to act. The amalgamation of energy and information technology (IT) advances with the growing of the renewable energy attractiveness have changed the energy services. The distributed energy resources (DER) is considered as a solution for buildings [International Renewable Energy Agency, 2019].

Over the last thirty five years, wind energy has been the answer to these issues. The design, implementation and enforcement of wind energy production is not limited to small-scale but has entered into a mature industrial sector. The wind is the most used among the renewable sources of energy. The reasons are the commercial acceptance, the low cost, the ease of operation and maintenance and the small adverse effect on the environment. However, as the size of the wind turbines becomes larger and larger, the rotor noise constitutes a barrier for the future development. The main purpose in the use of wind turbines is to achieve high aerodynamic performance [Zhu, 2016].

The most rapidly increasing energy sector is the wind power generation (Figure 1.3). By the end of 2012, the total installed capacity of wind turbines around the world was 285 GW. Researches take place worldwide, in order to increase the size, efficiency, reliability of the wind turbines and to decrease their costs, complexity, and all the related risks [Mamadaminov, 2013].

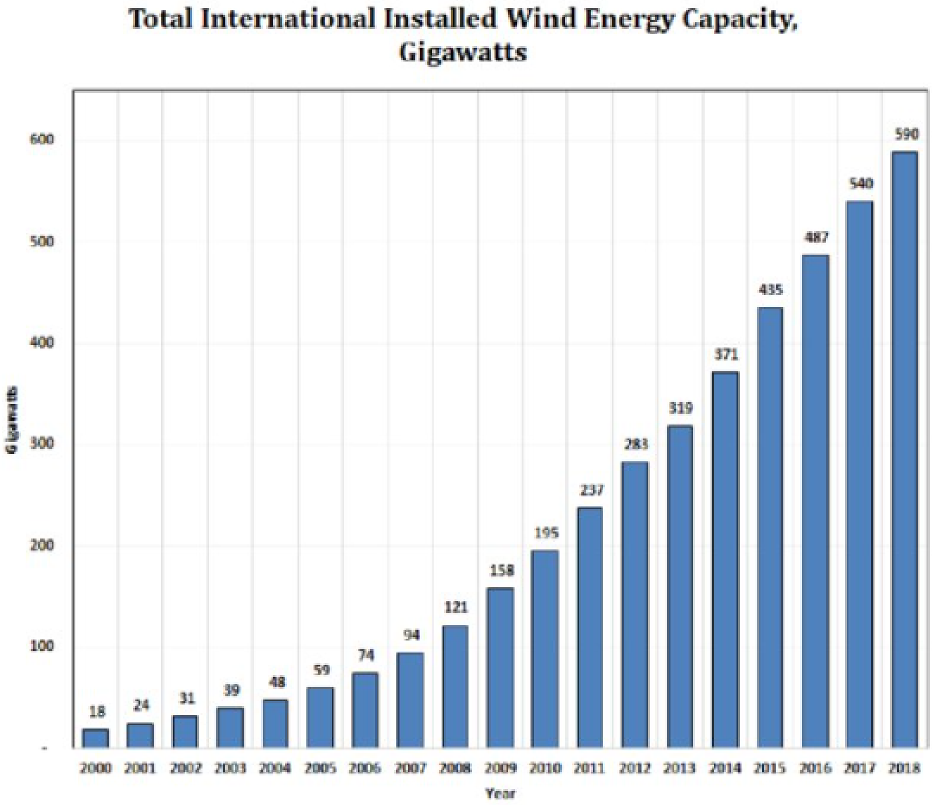


Figure 1.3 Global wind energy capacity growth.

One of the major problems of the wind industry is the aerodynamic design of the wind turbine blades. The design has an important impact on getting the maximum power out of wind. The wind turbine blades require specific design proceduires, in order to work well in different weather conditions and to be also controllable [Mamadaminov, 2013].

The first dedicated wind turbine blades were designed in the middle of 1980 for wind energy applications. The airfoils used in wind turbines are (in general) different from the ones used in aviation; they have higher design lift point, wider off-design capabilities and challenging structural integrity. Also, the airfoils with smooth post stall are mostly desirable for use in such applications [Mendez, 2014].

During the 1980s, initiated the development of special-designed airfoils for horizontal axis wind turbines (HAWTs) as a joint venture between the National Renewable Energy Laboratory (NREL), the Solar Energy Research Institute (SERI) and Airfoils Incorporated. After a decade, 9 airfoil families have been produced for wind turbines of various size [Mamadaminov, 2013].

As the wind speed increases with the elevation from the ground, a constant growing in the hub height and rotor diameter of HAWTs is taking place, along with their efficiency and controllability.

1.1 Background

The harvesting of wind energy goes back in time for many centuries. In China by 500 BC there were water pumps, while in Persia and Middle-East there were windmills with woven-reed blades, which grinded the grain.

By the 11th century, the people in the Middle-East created wind pumps and used the windmills for food production. The merchants were very important in the history of the wind power, because they "transfer" the knowledge of the wind technology to Europe. Therefore, the Dutch first developed wind pumps in order to drain the lakes along the Rhine River Delta. Continuously, the immigrants from Europe "traveled" the wind energy technology around the Western Hemisphere.

In America, they used the wind power during the 1800s and 1900s to grind grain, pump water and cut woods. Additionally, during the 1930s the wind pumps and the wind turbines were widely used. In fact, some ranches use till now the wind energy for be supplied with water.

In Denmark, very early wind turbines have been used for electricity production; by the end of the 20th century there were more than 2000 windmills that produced more than 30MW in the time that other nations were using the fossil fuels for their energy needs.

The situation has dramatically changed during the 1970s because of the increased pollution and the fuel crisis. The fuel crisis in the early 1970s changed dramatically the way that the governments around the world looked at the energy-production issues. In that time they were enforced to focus on more sustainable and efficient sources of energy. Nowadays, the wind turbines possess a wide and very important role in the life around the planet. More and more countries use the wind turbines on large (in-shore or off-shore) farms.

2. Wind turbines

A wide range of wind turbines are currently designed, manufactured and fabricated by different companies around the globe. The first classification of wind turbines is about their shaft orientation. A Horizontal Axis Turbine (HAWT) is the turbine with a shaft mounted horizontally, and parallel to the ground. A turbine with a vertical axis of rotation and a shaft normal to the ground is characterized as a Vertical Axis Wind Turbine (VAWT).

A typical HAWT consists of these main parts: blades, rotor, nacelle unit, tower and gear box. Figure 2.1 depicts a detailed description of the main parts of a HAWT. In Figure 2.2 a comparison between HAWT and VAWT designs is presented.

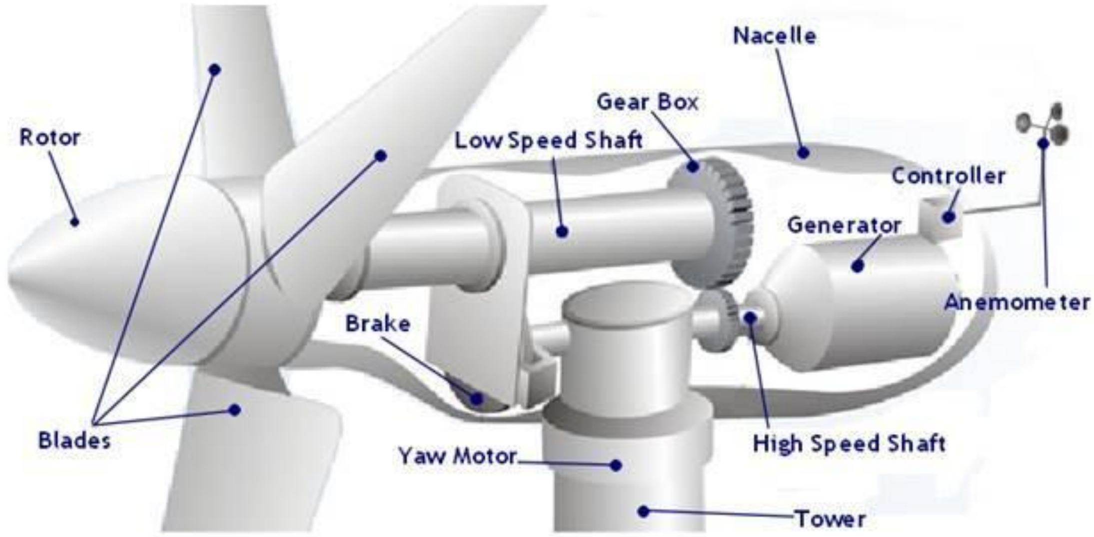


Figure 2.1 The most important parts of a HAWT [Source: eepowerschool.com].

Generally, the wind velocity growths as the height increases due to the shear layer of the wind close to the ground. The price tag of energy that is harvested from the wind turbine decreases with increasing the wind turbine (actually its hub height and its rotor diameter). However, these cannot be increased beyond a specific limit, due to structural integrity problems, due to the increased weight and mass of the blades and of the nacelle, the technical restrictions related to the installation procedure of the wind turbine itself, and, finally, material stability limitations. In contrast, the quest for more energy necessitates more efficient wind turbines. Therefore, the increase of the wind turbine efficiency and energy production is of great importance, thus, a great effort is spent for improving the turbine blades, their aerodynamic design and their construction with new, lighter and stronger materials, and better manufacturing processes, with lower cost, better efficiency, and better impact to the environment.

A wind turbine is a device that converts the wind's kinetic energy into usable electrical energy [https://en.wikipedia.org/wiki/Wind_turbine]. Furthermore, the wind turbine has to be a reliable machine that doesn't cost a fortune. It has to be constructed so as to work continuously for long time periods without the need for servicing. The wind turbines can be separated into several categories. The criteria of those categories could be the position of the axis, the number of the blades but also we can add the rated speed. Furthermore, we can separate the wind turbines based on their size and the electrical power that they produce.

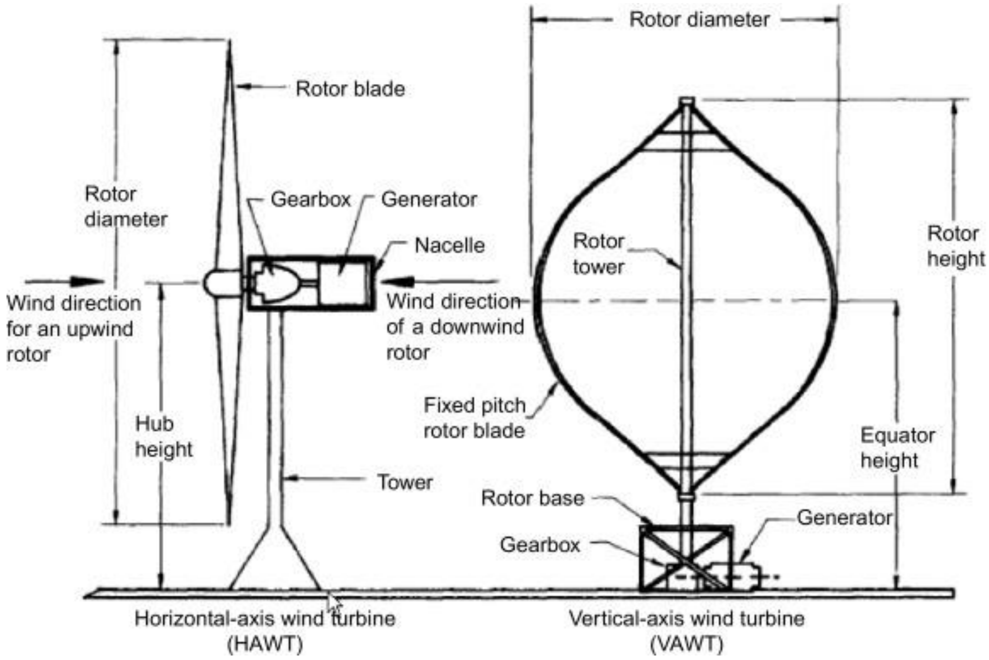


Figure 2.2 The comparison between HAWT and VAWT designs [Source:sciencedirect.com].

2.1 Horizontal axis wind turbines (HAWTs)

Horizontal axis wind turbines (HAWTs) (Figure 2.3) consist the most common type of wind turbines. The main components are: the rotor, the nacelle, the tower, and the foundation.

There are many advantages of using this type of wind turbines. In the onshore wind energy are:

- ✓ It has foundations of lower cost.
- ✓ Easily combined with electrical-grid network.
- ✓ Cheap installation and access during the construction phase.
- ✓ Easily and cheap maintenance.

In contrast to the disadvantages, which are the following :

- ✓ Negative visual impact.
- ✓ Noise pollution.
- ✓ Limited availability of land.
- ✓ Restrictions about obstructions like land, buildings, etc.
- ✓ Affected by more turbulence.

For off-shore wind energy production, the advantages are:

- ✓ Easy installation in the water.
- ✓ Established far away from the shores so the noise pollution isn't a problem.
- ✓ Less affected to more turbulence in wind and low wind shear.

The corresponding disadvantages are :

- ✓ Installation is very expensive and complex.
- ✓ Connection to the utility grid is expensive and complex.
- ✓ Operation and maintenance is complex.

Generally, the horizontal axis wind turbines have achieved ***high power output***, ***high efficiency***, ***high reliability and high operating wind speed***.

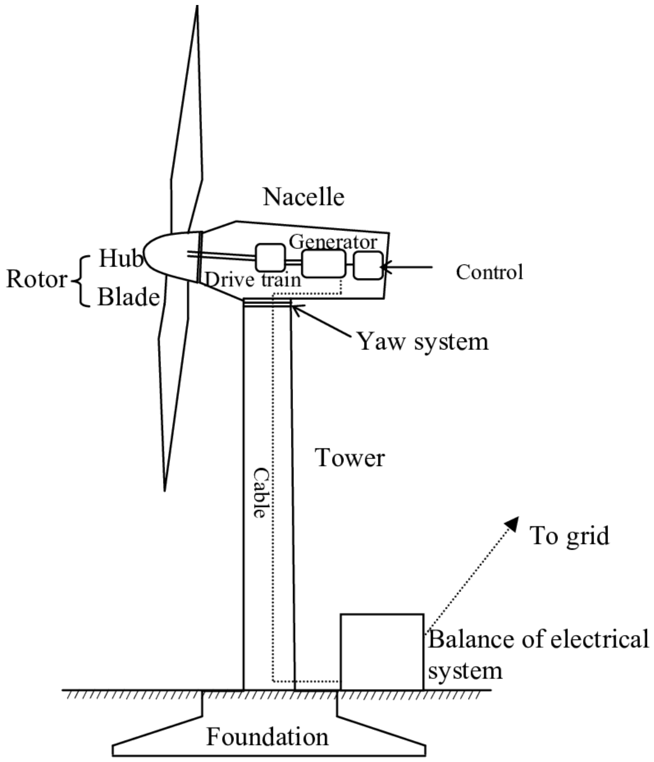


Figure 2.3 The main parts of a HAWT [Source: researchgate.com].

2.2 Vertical axis wind turbine (VAWT)

The Vertical Axis Wind Turbine (VAWT) is a wind turbine type where the main rotor shaft is positioned transverse to the wind; as a result, the main components of the wind turbine are located at the base of the turbine, with some obvious advantages. There are two types of VAWTs: i) the Savonius wind turbine type and ii) the Darrieus wind turbine type [https://en.wikipedia.org/wiki/Vertical-axis_wind_turbine].

There are many advantages of using this type of wind turbines:

- ✓ The inherent omnidirectional natural of the rotor.
- ✓ The closer spacing between turbines.
- ✓ Smaller starting wind speed.
- ✓ Smaller environmental impact.
- ✓ Easy maintenance and installation.
- ✓ Fewer restrictions for the installation.
- ✓ Remarkable shape.

In contrast, the disadvantages are the following:

- ✓ Less rotational efficiency.
- ✓ Lower available wind speed.

- ✓ Component wear.
- ✓ Lower efficiency.
- ✓ Need for self-starting mechanism.

2.2.1 Savonius type

The Savonius wind turbine is a type of VAWT (Figure 2.4) characterized by the S-Shape of its blades. It was invented in Finland in the 1922 by Sigurd Savonius. Also, it can have two, three or more scoops. It is very useful in applications like grinding grain, pumping water etc.

There are many advantages of using Savonius wind turbines:

- ✓ Always face into the wind no matter the wind direction
- ✓ It isn't necessary a mechanism to make the turbine facing the wind
- ✓ Low speeds so is less dangerous for the wildlife
- ✓ Not affected by turbulence

In contrast to the disadvantages that are:

- ✓ Low efficiency
- ✓ Less power generation

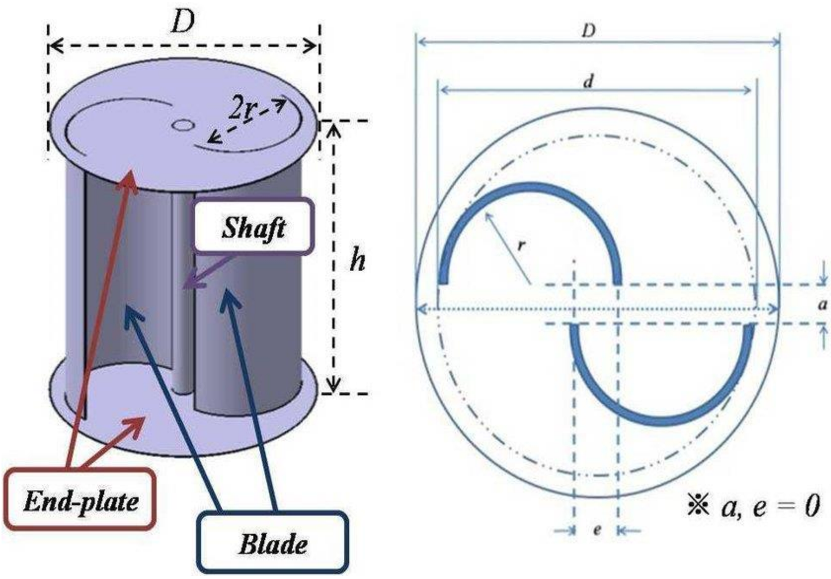


Figure 2.4 Shape of Savonius type wind turbine.

2.2.2 Darrieus type

The Darrieus wind turbine (Figure 2.5) is a type of vertical axis wind turbine (VAWT). The wind turbine involves curved or straight blades mounted on a vertical rotating axis. In the original versions, the airfoils are symmetrical with zero rigging angle, in order to be moved in any wind direction. The design of the Darrieus wind turbine was invented by Georges Jean Marie Darrieus in 1931, who was a French aeronautical engineer [Sharma, 2015].

The Darrieus rotor is spinning in a way that its aerofoils move forward to the air in a circular path. The oncoming airflow has as a result a small positive angle of attack (AoA) to the blades. The aerodynamic principles are the same with the way that a helicopter moves in autorotation [Sharma, 2015]. The generated force is indirectly to the direction of the wind as the wings are symmetrical and the rigging angle is zero. The rotor spins irrelatively to the wind speed and faster. The energy that arises from the torque and the speed may be converted into power that can be used by an electrical generator [Sharma, 2015].

There are two categories of blades: i) the curved blades (Figure 2.6) and ii) the straight blades (Figure 2.7).

There are many advantages of using Darrieus wind turbines:

- ✓ Reclaim all the type of the wind directionς.
- ✓ The appearance of this type of windmill is much preferred than horizontal axis windmill.
- ✓ Easily integrated into buildings.
- ✓ No need for brushes in order to have large twisting angles.

In contrast, the disadvantages are:

- ✓ Difficulty in starting.
- ✓ Low efficiency.

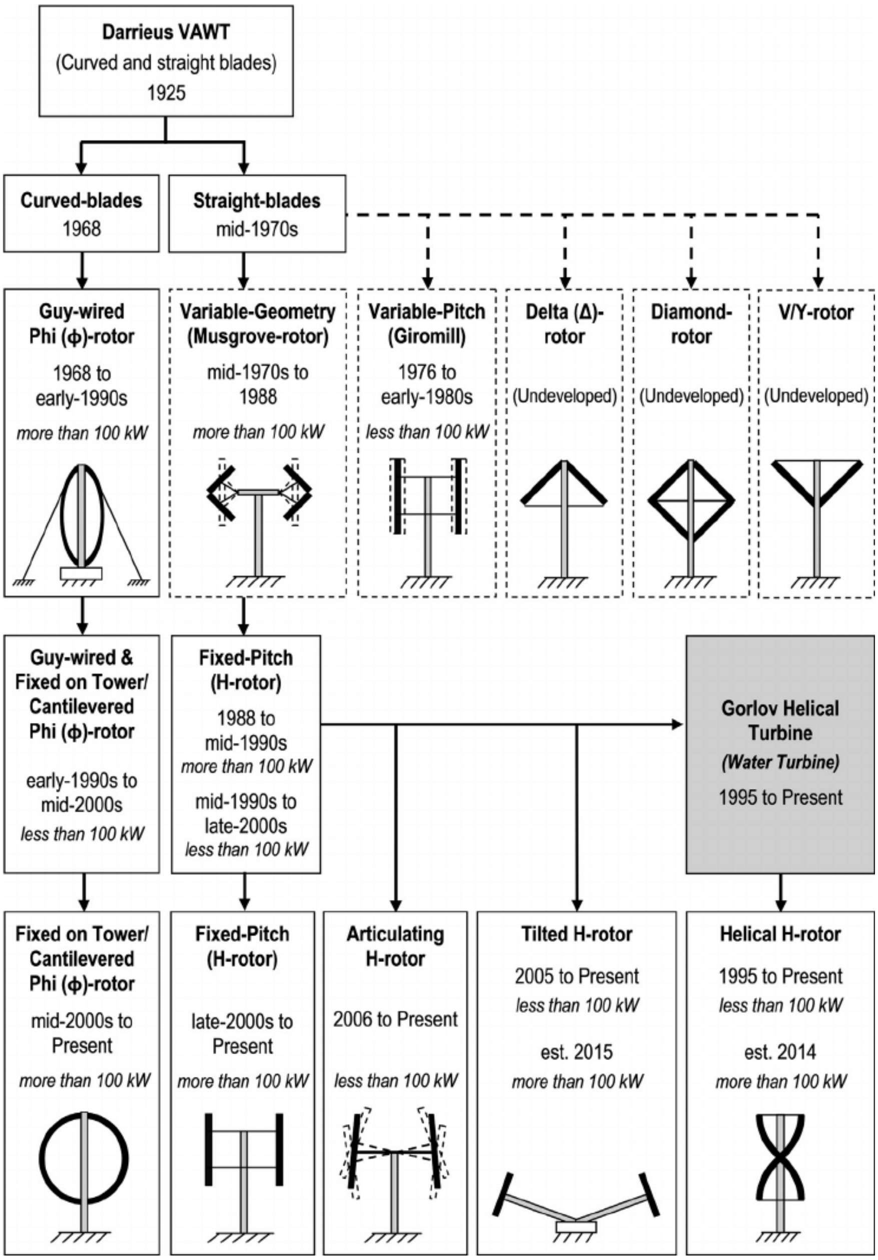


Figure 2.5 Timeline of Darrieus wind turbine development.

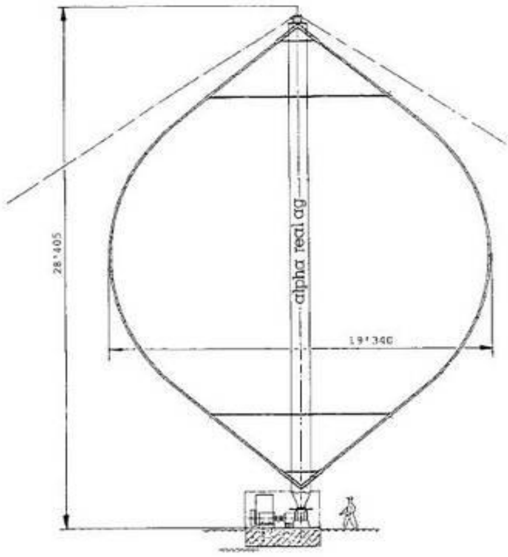
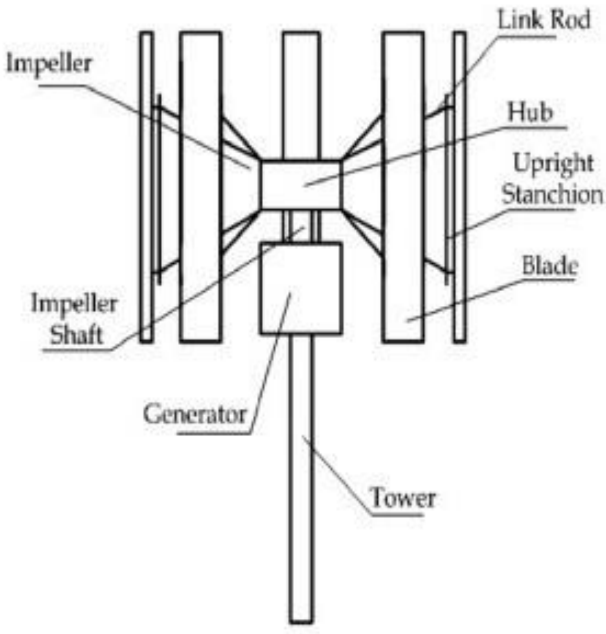


Figure 2.6 A Darrieus VAWT with curved blades [Source: wind-works.org].



(b)

Figure 2.7 A Darrieus VAWT with an H-rotor.

2.3 Number of blades

If the wind turbines are compared in relation with the number of the blades, they can distinguished into two categories: 1) small blade number 2) multi-blade.

In the small blade number category, the wind turbine has one to three blades. They have a higher power factor than the large blade number turbines category and show optimal operation at high values of speed. However, they have higher noise. The wind turbine with one blade is cheaper and with a lower efficiency of 10% than the two-blade one. The triple-blade turbine performs better than the two-blade one by 5%.

The multi-blade category has more than three blades. The diameter of their rotor is small, resulting in low peripheral speed and high torque. Their cost is slightly higher than the high speed wind turbine with small blade number.

2.4 Rated speed of the rotor

The wind turbines can be separated also in relation to the rated speed of the rotor. As rated speed we can refer to the wind speed that the turbine hits its maximum capacity in output power.

The design of most wind turbines is based in the logic to increase the power output. However, an additional target is to prevent the generator from producing more power than the designed one. The most common cause of such a situation is the wind gusts, which can cause sudden accelerations of the rotor. Other causes can be:

- The air density that is affected by altitude, humidity, temperature.
- The yaw and pitch response.
- The SCADA programming.

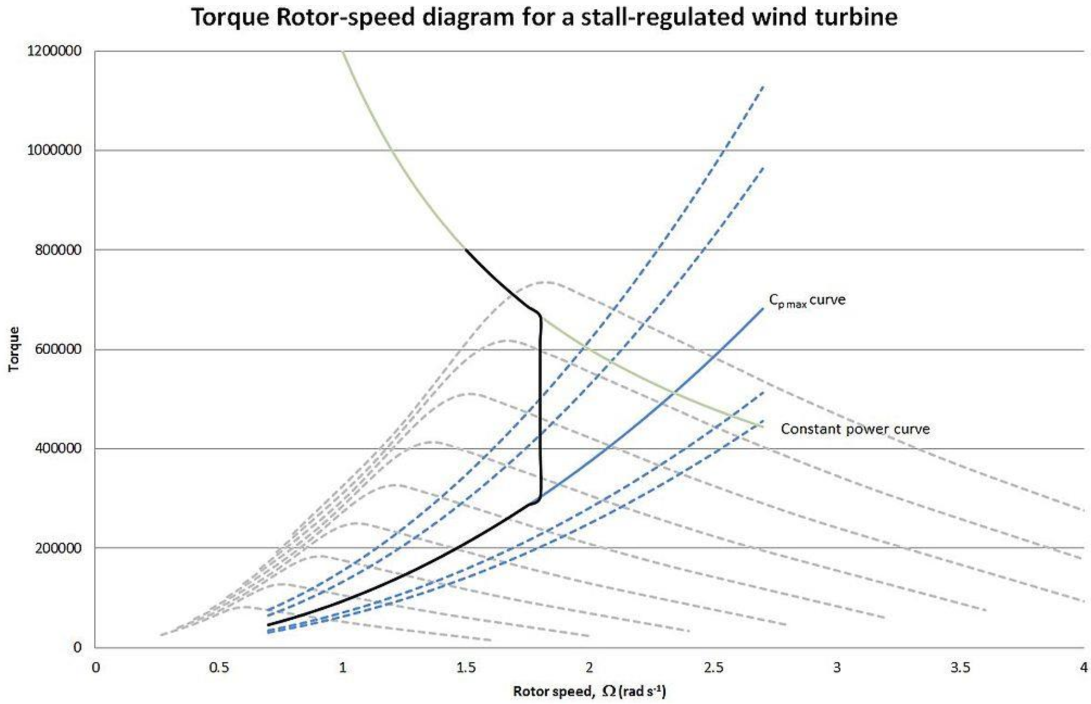


Figure 2.8 Diagram of torque rotor- speed for a stall- regulated wind turbines

2.5 Size of the wind turbine

2.5.1 Small wind turbines

Small wind turbines (recognized also as Micro Wind Turbines) are the wind turbines that operate between 1000 W (1 kW) and 300 kW. Technically speaking, the rotor of a small wind turbines has a diameter approximately 1.5 to 3.5 m (4 ft 11 in- 11ft 6in). The small wind turbine produces between 500 W and 10 kW of power [https://en.wikipedia.org/wiki/Small_wind_turbine].

The generators of the small wind turbines are generally three-phase alternative current (AC) while the induction type generators are usually used. The majority of the small wind turbines work at a minimum wind speed of 4 m/s but there are also small wind turbines that work at lower wind speeds.

2.5.2 Medium wind turbines

Medium wind turbines are those that operate from 600 kW to 1.2 MW. Those turbines are single installations on a farm, a domestic property or a small business. They provide electricity for on-site usage.

Some reasons for the use of small and medium wind turbines are the following [http://drømstørre.dk/wp-content/wind/miller/windpower%20web/en/tour/wtrb/size.htm]:

1. The local electrical grid sometimes is too weak to handle the electricity output from a large machine.
2. Smaller machines may be an advantage in a weak electrical grid.
3. Several small machines spread the risk in case of temporary machine failure.
4. Aesthetical landscape considerations.

2.5.3 Large wind turbines

Large wind turbine are selected in the following cases [http://drømstørre.dk/wp-content/wind/miller/windpower%20web/en/tour/wtrb/size.htm]:

1. In the areas that is difficult to find sites for more than a single machine, the large turbine with a tall tower uses the wind power more efficiently.
2. They are well suited for off-shore wind power harvesting.
3. The larger machines are able to deliver electricity at a lower cost than smaller ones (higher efficiency).
4. The have access to higher wind speeds at higher altitudes.

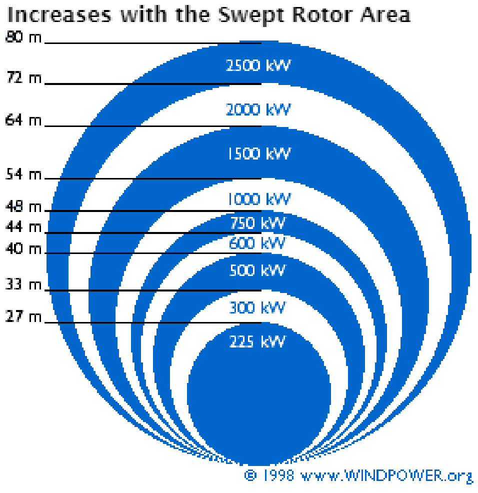


Figure 2.9 Variation of the wind turbine power with its swept rotor area.

2.6 Electrical power

The low-power type wind turbines produce from 50 W to 30 kW. They have a starting speed of about 4.5 m/sec and a cost of around 2000 Euros per kW. The installation of such type of wind turbines is located in isolated areas, which are not connected to the electricity grid.

The medium-power wind turbines produce from 30kW to 350 kW. They usually have a starting speed of about 5.1 m/sec with a cost of 1000 Euro per kW. The installation of this type of wind turbines is located in small communities for distributed generation and for hybrid systems.

The high-power wind turbines produce power greater than 350 kW, with a cost of 1000 Euro per kW and a starting wind speed of 5.8 m/sec. They are located in wind farms. [IRENA , 2012].

3. Airfoils for Wind Turbines

In order to achieve the maximum power production, it is important to achieve a lift-to-drag ratio as high as possible, especially for the airfoils that are used on the outer part of the blades. In pitch regulation and active stall regulation wind turbines, the lift-to-drag ratio should be high in the operational range of the turbine [Dahl, 1998].

It is required that the operational point to be close to the maximum lift, so as to ensure high lift-to-drag ratio below stall for stall regulation. If wind gusts exist, for pitch regulation it can ensure also the reduction of power peaks [Dahl, 1998].

Unfortunately, wind turbine blades get dirty at their leading edge, due to the presence of bugs and dirt. This phenomenon increases the surface roughness at the leading edge of the blades, which will cause early transition from laminar to turbulent boundary layer, and therefore a jump in the boundary layer momentum thickness. As a result, a reduction of the maximum lift is produced, as well as a lowering of the lift curve slope and an increase of the skin friction. In the case that stall regulation is required, the maximum lift coefficient must be insensitive to leading edge roughness [Dahl, 1998].

As it can be understood, the design and/or selection of the optimal airfoils is not a trivial task. The desirable airfoil characteristics are a combination of aerodynamic and structural properties, along with other characteristics. Contradictory requirements also exist. For example, high lift-to-drag ratio is in contrast to high airfoil thickness. High maximum lift is in contrast to insensitivity to leading edge roughness. High lift-to-drag ratio at the Design Point is very difficult to obtain at the same time with extensive off-design requirements [Dahl, 1998].

3.1 NACA Series Airfoil Families

In the beginning of the airfoil design, the designers used their knowledge and their experience in order to design and/or modify the shape of an airfoil. Later on, the National Advisory Committee for Aeronautics (NACA) developed several series of airfoils, mainly for airplane applications. The 4-Digit and the 5-Digit airfoil series and the modified series of them were created using analytical equations to describe the camber (curvature) of the mean-line and the section’s thickness distribution along the length of the airfoil. Some years later, the 6-Digit airfoil series were created with more complicated shapes, which have been produced by using a more theoretical basis rather than geometrical methods.

An airfoil is composed by the upper and the lower surface. An airfoil family is based on a number of parameters like (Figure 3.1):

- Its maximum thickness.
- Its maximum camber.
- The position of maximum thickness.
- The position of maximum camber.
- Its nose radius.

Eastman Jacobs in the early 1930s, used polynomials with a certain degree and the above parameters in different types of aircraft. The NACA airfoil family have as a basis a distribution of mean-line (geometric centerline) and a distribution of thickness. The mean-line creates the curvature of the airfoil. The final shape of airfoil emerges from the placement of the circles (that have as radius the distribution of thickness in a specific point) in the mean-line. The area that is surrounding to the circles is the final airfoil [Amoiralis, 2004].

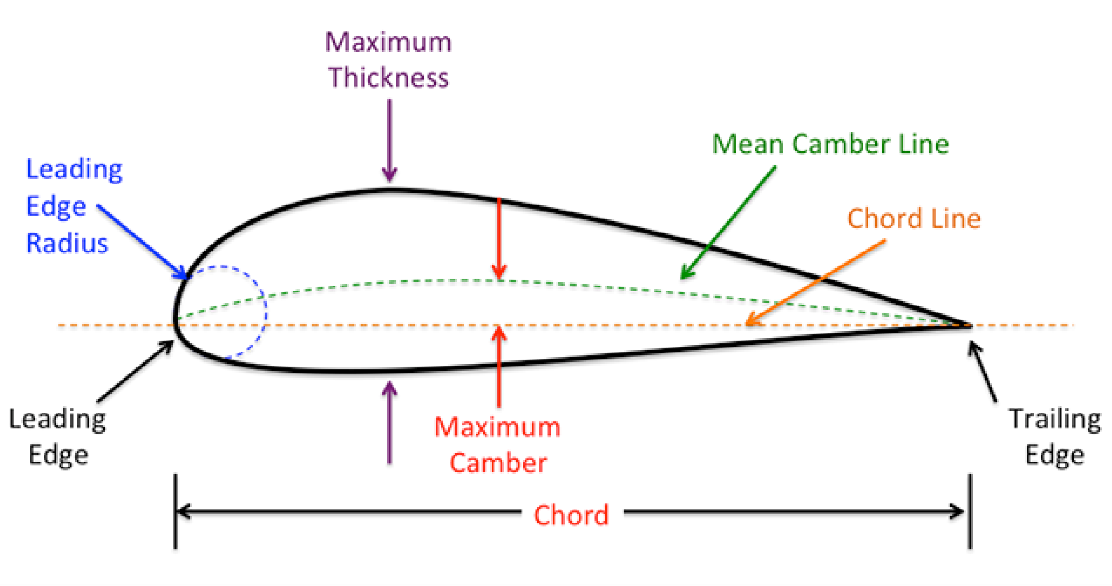


Figure 3.1 The main characteristics of an airfoil [Source: https://www.geniuserc].

3.1.1 4 -Digit Airfoils

The 4-Digit airfoil series is controlled by 4 digits (NACAMPXX) which designate the camber, the position of the maximum camber, while the final 2 digits define the thickness. As an example [Amoiralis, 2004], NACA 2412 means:

- M is the maximum camber divided by 100. So, M=2 means that the camber is 0.02 or 2% of the chord.
- P is the position of the maximum camber divided by 10. So, P=4 means that the maximum camber is at the location of 0.4 or at 40% of the chord.

- XX is the thickness divided by 100. So, 12 means that the thickness is 0.12 or 12% of the chord.

3.1.2 5-Digit Airfoils

The 5-Digit airfoil series (NACA LPQXX) is controlled by the same thickness envelope as 4-Digit series but with a different camber line and numbering system. An example is presented [Amoiralis, 2004], for the NACA 23012 airfoil:

- L controls the camber. It indicates the designed Lift Coefficient (CL) multiplied by 3/20. So, L=2 means that the CL=0.3.
- P is the position of the maximum camber divided by 20. So, P=3 means that the maximum camber is at the location 0.15 or 15% of the chord.
- Q reflects the camber line. Therefore, Q=0 means that the camber line coincides with the chord.
- XX defines the maximum thickness. Therefore, XX=12 means that the maximum thickness is 0.12 or 12% of the chord.

3.1.3 NACA Modified 4- Digit and 5-Digit Airfoil Series

In NACA Report 492, the 4-Digit (NACA MPXX-AA) and the 5-Digit (NACA LPQXX-AA) airfoil series were subjected to modifications. These modifications allow the designer to choose the position of the maximum thickness and the leading edge radius.

The modifications are showed by a suffix consisting of a dash and two digits. Therefore, they can change the leading edge radius and the position of the maximum thickness. In addition, the first integer indicates the roundedness of the leading edge. The value 0 indicates a sharp leading edge and a value of 6 indicates that the nose radius is the same as the original. In case that this number is increased, indicates a more rounded nose. The second integer indicates the position of the maximum thickness in the chord in tenths. The default location for all 4-digit and 5-digit is 30% back from the leading edge.

For example, NACA23015-64 Airfoil means:

- The maximum thickness is 15%.
- There is a 230 mean line.
- There is a leading edge radius corresponding to an index of 6.
- The position of maximum thickness is at 40% of the chord.

3.1.4 NACA Modified 6-6A Digit Airfoils

For the production of this type of airfoils, the thin airfoil theory is used. The curvature line of 6-Digit NACA airfoils was designed under the rules of the thin airfoil theory in order to produce a constant loading from the leading edge till the position of x/c=a. Afterwards, the loading from the leading edge reduces till to be zero in the trailing edge of the airfoil. Theoretically, the loading in the leading edge has to be either zero, or infinite, based on the thin airfoil theory.

The 6-Digit airfoils were created having the inclination of middle line constant in the front of the point x/c=0.005 and equal to the value of this point.

The mean line is given by analytical equations. The thickness is given by inverse design numerical methods, based on the desired aerodynamic loading. The 6-Digit NACA Airfoil is described by 6 digits.

For example, NACA 65, 3-218, a=0,5 means:

- 6 is the definition of airfoil series.
- 5 indicates the position with the least pressure (in tenths) behind of the leading edge for symmetrical zero lift.
- The number 3 after the comma (sometimes is underlined or in parentheses) gives the order of the lift coefficient in tenths, above and below from the design lift coefficient, in which favorable pressure gradients exist on both surfaces. 2 indicates the lift coefficient in tenths of the design point.
- The last 2 digits indicate the thickness of the airfoil as a percentage of chord.
- a indicates the type of the mean line. In case that we don’t know the type of the mean line, it is common to use the flat line that corresponds to a=1.

The 6A-Digit Airfoil adopts the modification of a=0.8 in order to allow the construction of a straight line near the leading edge.

3.1.5 Advantages and disadvantages of the NACA Airfoils

Family	Advantages	Disadvantages	Applications
4-Digit	1. Good stall characteristics 2. Small center of pressure movement across large speed range 3. Roughness has little effect	1. Low maximum lift coefficient 2. Relatively high drag 3. High pitching moment	1. General aviation 2. Horizontal tails ***Symmetrical:*** 3. Supersonic jets 4. Helicopter blades 5. Shrouds 6. Missile/rocket fins
5-Digit	1. Higher maximum lift coefficient 2. Low pitching moment 3. Roughness has little effect	1. Poor stall behavior 2. Relatively high drag	1. General aviation 2. Piston-powered bombers, transports 3. Commuters 4. Business jets
16-Series	1. Avoids low pressure peaks 2. Low drag at high speed	1. Relatively low lift	1. Aircraft propellers 2. Ship propellers
6-Series	1. High maximum lift coefficient 2. Very low drag over a small range of operating conditions 3. Optimized for high speed	1. High drag outside of the optimum range of operating conditions 2. High pitching moment 3. Poor stall behavior 4. Very susceptible to roughness	1. Piston-powered fighters 2. Business jets 3. Jet trainers 4. Supersonic jets
7-Series	1. Very low drag over a small range of operating conditions 2. Low pitching moment	1. Reduced maximum lift coefficient 2. High drag outside of the optimum range of operating conditions 3. Poor stall behavior 4. Very susceptible to roughness	Seldom used
8-Series	Unknown	Unknown	Very seldom used

Figure 3.2 Advantages and disadvantages of NACA Airfoils [source: http://www.aerospaceweb.org/question/airfoils/q0041.shtml]

3.2 NREL Series Airfoil Families

The NREL Airfoils (Figure 3.3) were designed with the method of determining the nature of two dimensional viscous flow around an airfoil. Professor Richard Eppler is behind the development of the NREL airfoil family. The application of NREL family is common in various commercial wind turbine blades. The NREL blade families provide significant increase in the production of energy, because they provide less sensitivity to roughness effects, and better lift-to-drag ratios [Mamadaminov, 2013].

Blade Length (meters)	Generator Size (kW)	Thickness Category	Airfoil Family (root———tip)			
1-5	2-20	thick		S823		S822
5-10	20-150	thin		S804	S801	S803
5-10	20-150	thin	S808	S807	S805A	S806A
5-10	20-150	thick		S821	S819	S820
10-15	150-400	thick	S815	S814	S809	S810
10-15	150-400	thick	S815	S814	S812	S813
15-25	400-1000	thick		S818	S816	S817

Figure 3.3 NREL Airfoil Families for HAWT's.

3.2.1 S822/S823

The NREL S822/S823 thick airfoil families were designed for wind turbine applications. For the NREL S822/S823 airfoils, the S822 is for the tip of the blade and the S823 is designed for the root of the blade. The section characteristics are shown in the following Figures 3.4 to 3.15, and the corresponding diagrams (for various Reynolds numbers).

The airfoil requests for small stall-regulated HAWTs are the same with those of variable pitch HAWTs. Nevertheless, there is a special requirement for their blades. The airfoils that are used in stall-regulated wind turbines should be insensitive to roughness, in order to minimize the loss of the peak power. So, the S822/S823 airfoils are insensitive to roughness and most appropriate for stall regulated HAWTs [Somers, 2005].

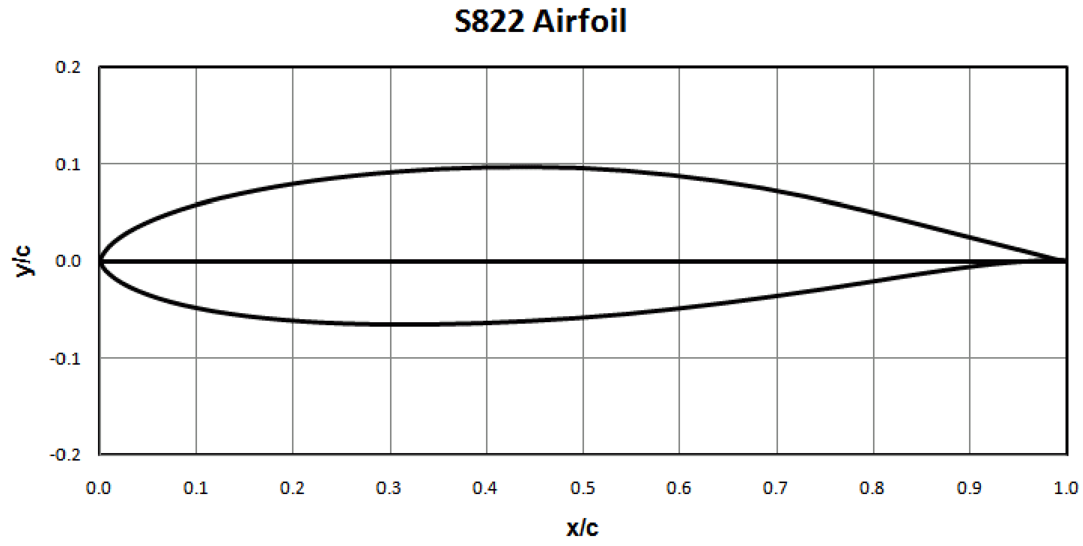


Figure 3.4 The S822 Airfoil.

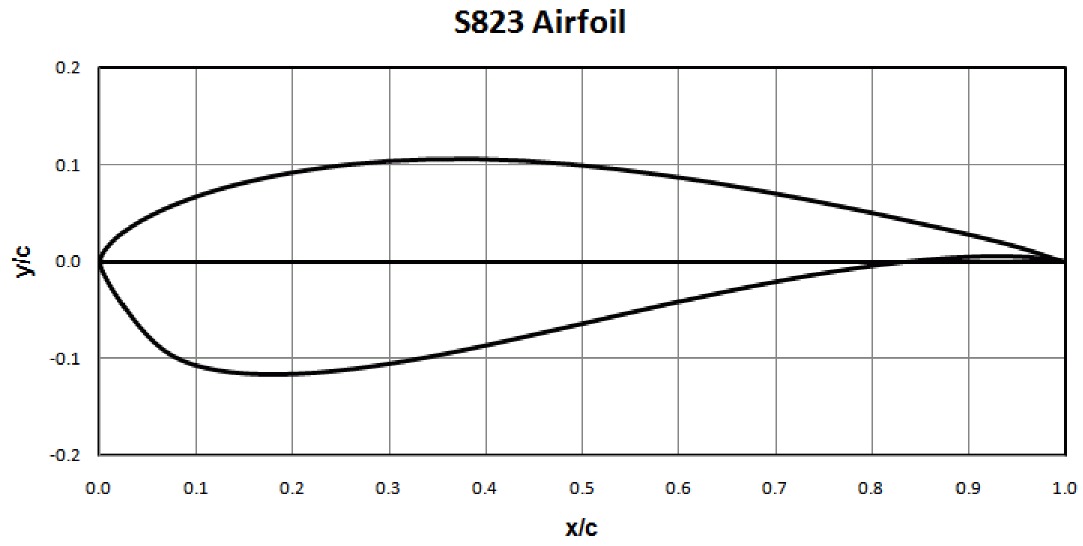


Figure 3.5 The S823 Airfoil.

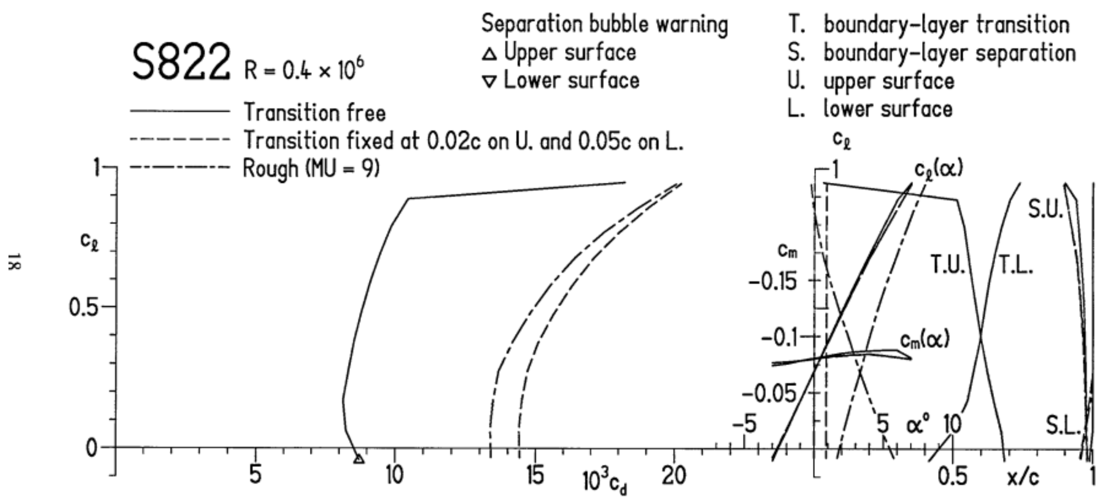


Figure 3.6 Section Characteristics of the S822 Airfoil ($Re=0.4x10^6$).

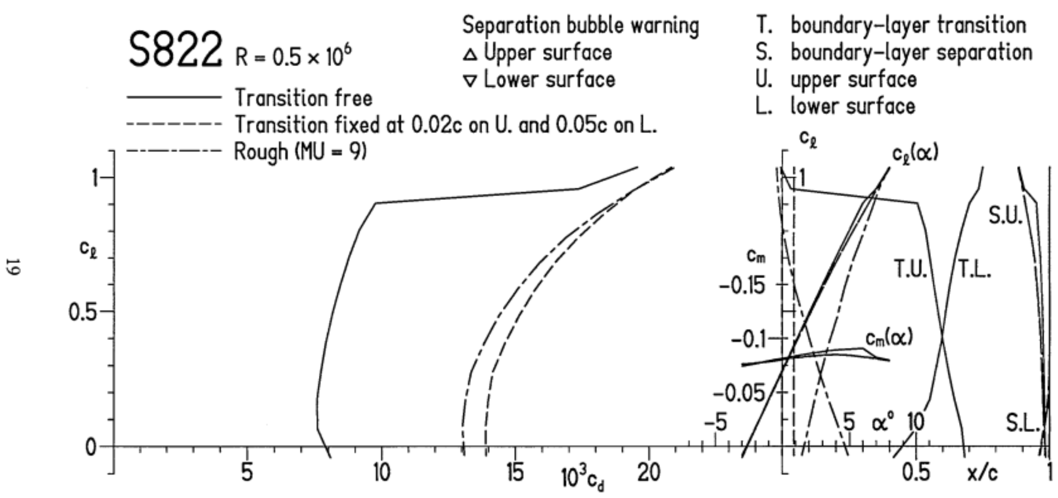


Figure 3.7 Section Characteristics of S822 Airfoil ($Re=0.5x10^6$).

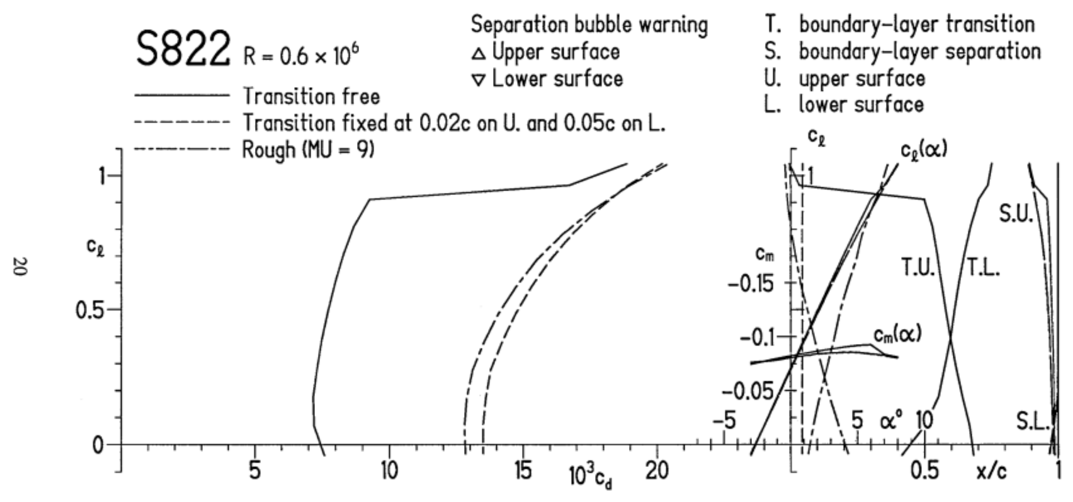


Figure 3.8 Section Characteristics of S822 Airfoil (Re=0.6x10[6]).

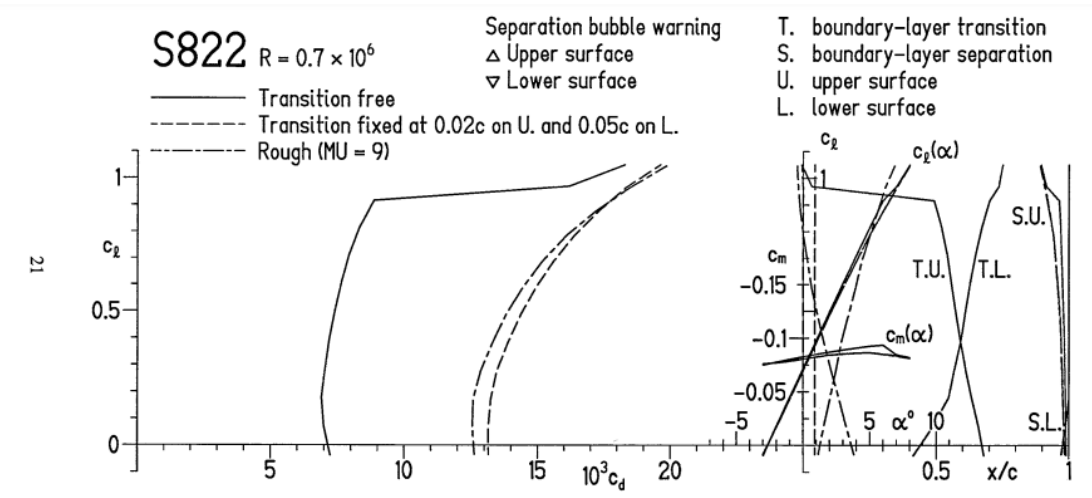


Figure 3.9 Section Characteristics of S822 Airfoil (Re=0.7x10[6]).

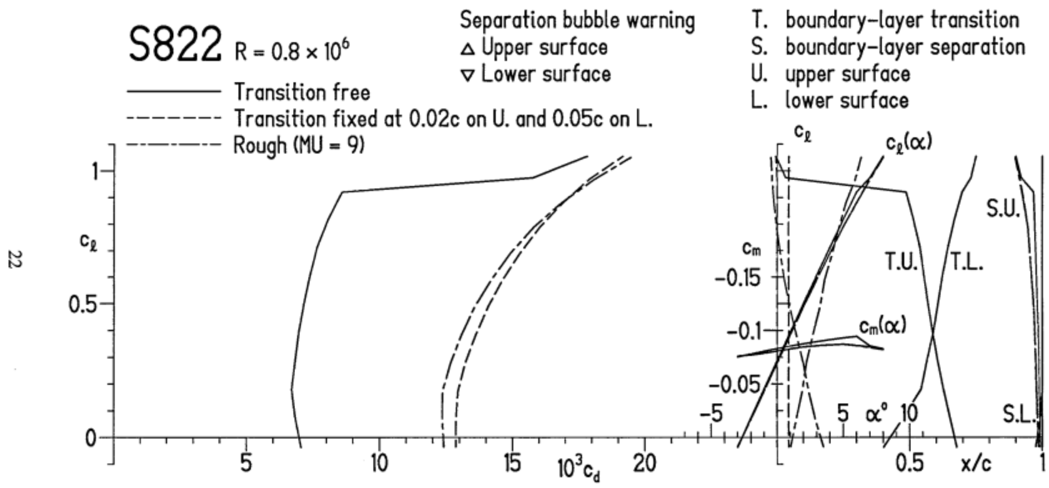


Figure 3.10 Section Characteristics of S822 Airfoil (Re=0.8x10[6]).

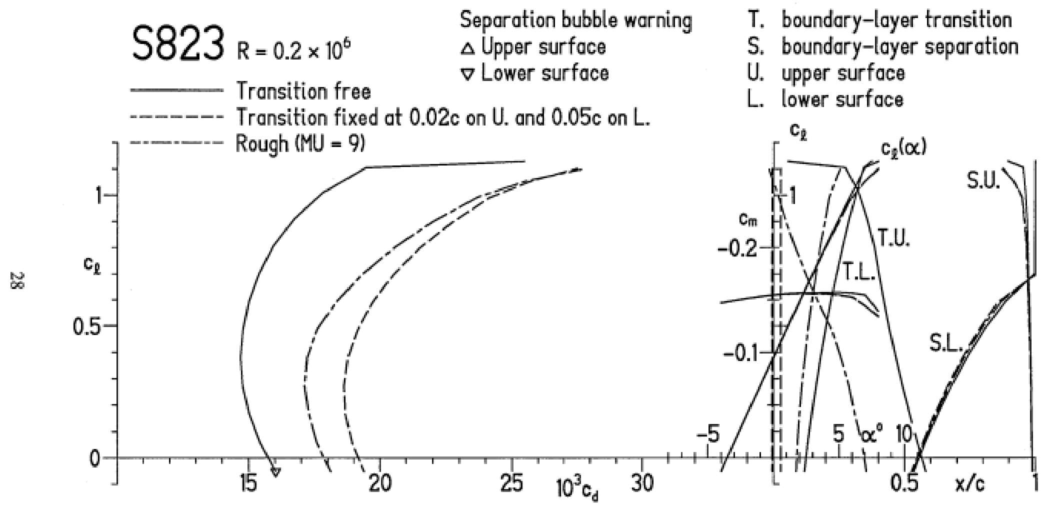


Figure 3.11 Section Characteristics of S823 Airfoil (Re=0.2x10[6]).

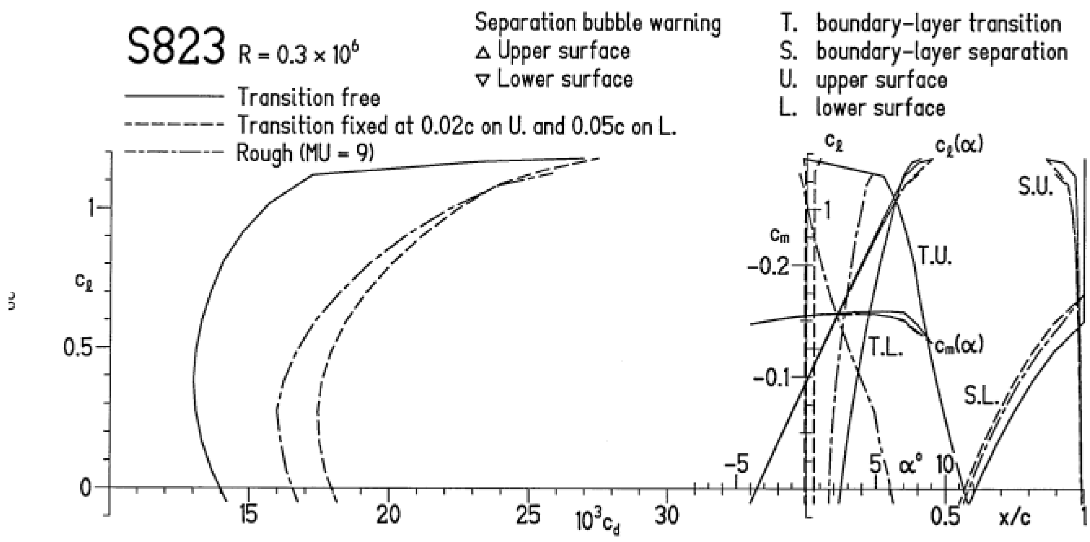


Figure 3.12 Section Characteristics of S823 Airfoil (Re=0.3x10⁶).

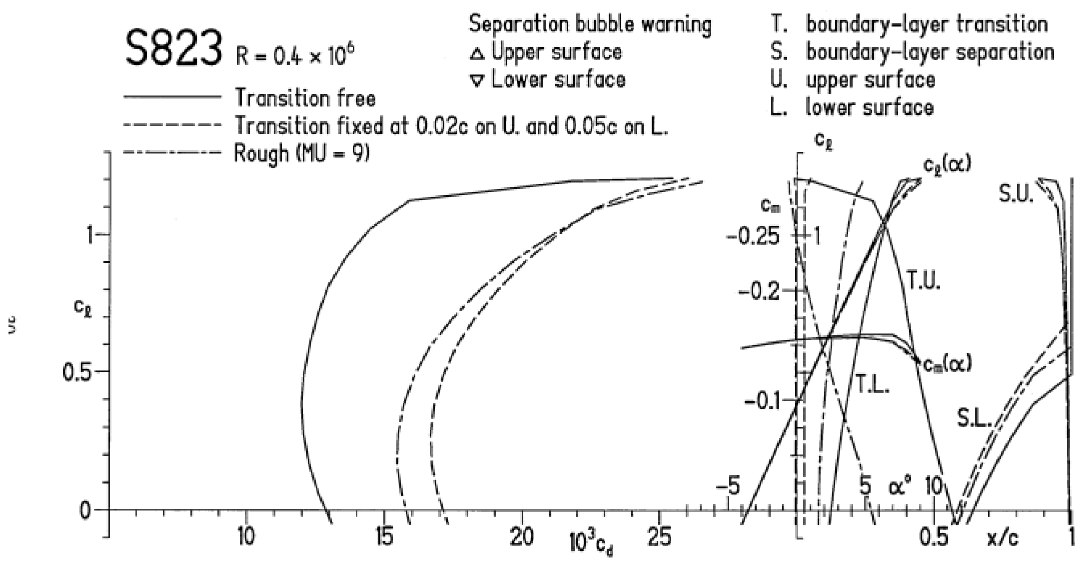


Figure 3.13 Section Characteristics of S823 Airfoil (Re=0.4x10⁶).

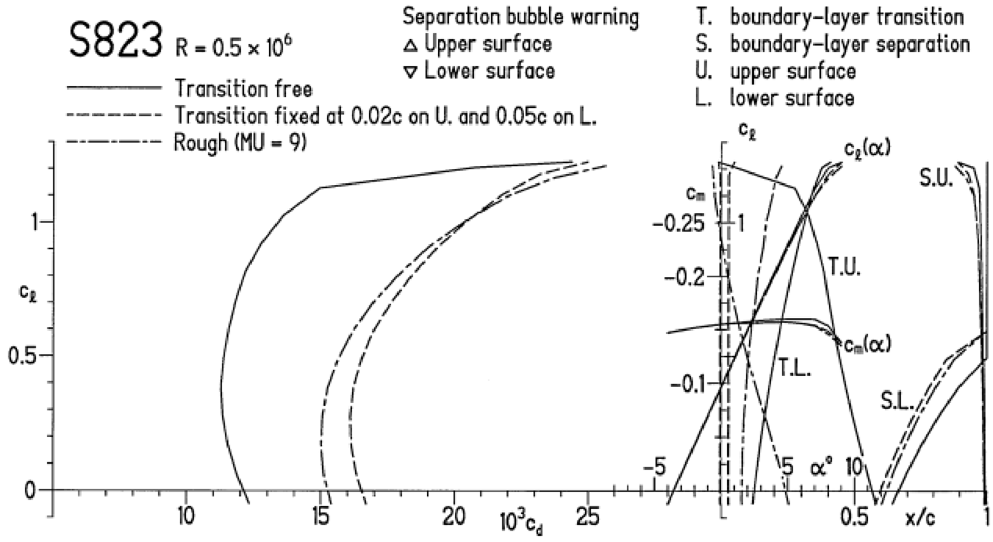


Figure 3.14 Section Characteristics of S823 Airfoil (Re=0.5x10⁶).

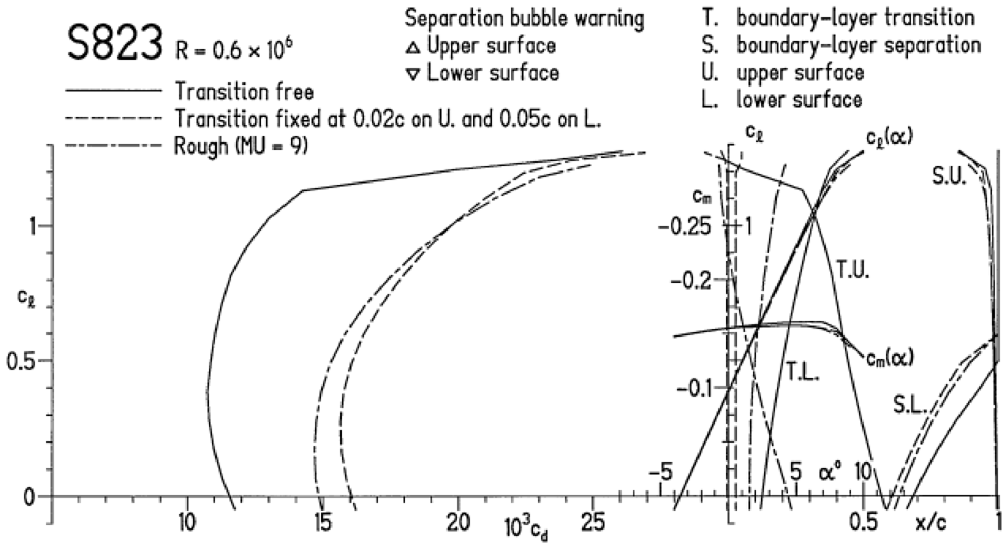


Figure 3.15 Section Characteristics of S823 Airfoil (Re=0.6x10⁶).

3.2.2 S801/S803/S804 Airfoils

This airfoil family is characterized by tip airfoils with high design lift coefficient $C_{1,max}$. It is suitable for variable pitch turbines that have low blade solidity. Also, it is suitable for variable – rpm turbines with low blade solidity. It has been developed for medium-size wind turbines that are in the range of 20-100 kW [Tangler, 1995].

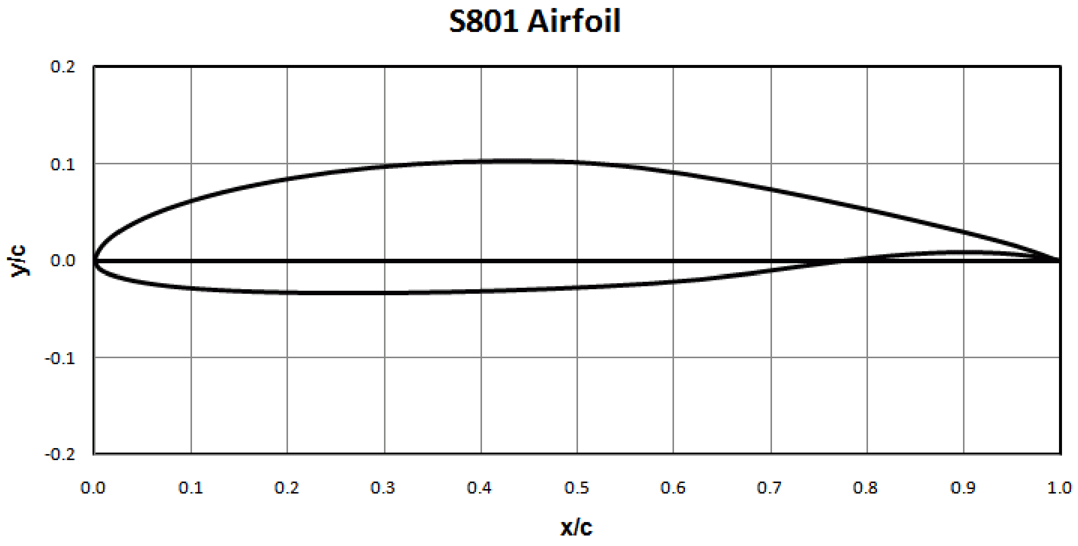


Figure 3.16 The S801 Airfoil.

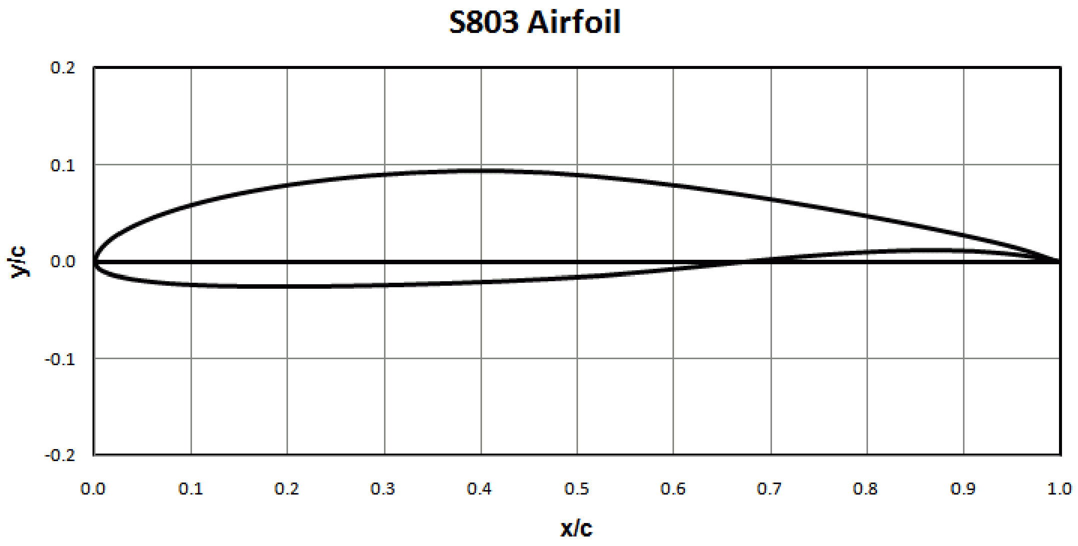


Figure 3.17 The S803 Airfoil.

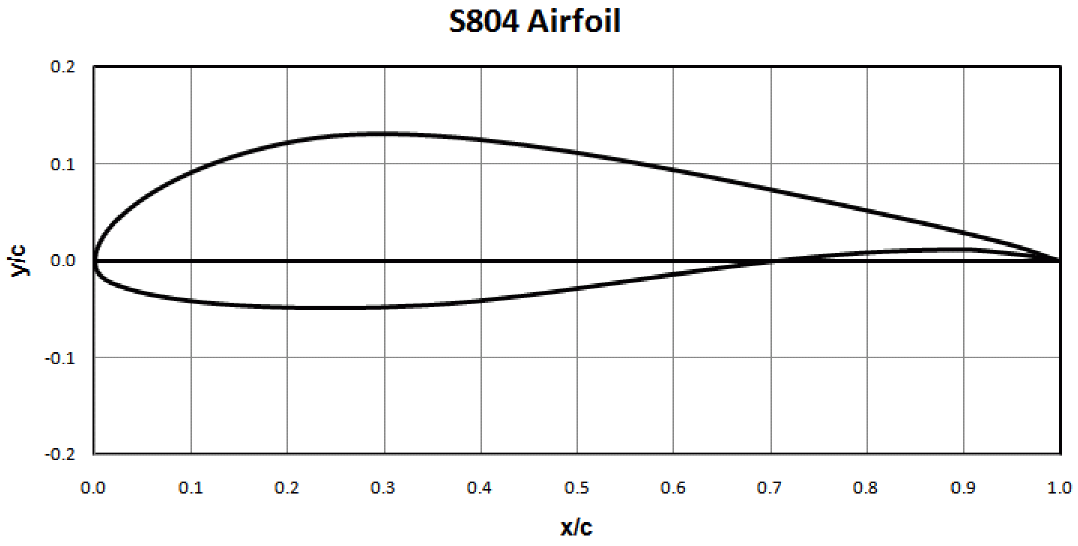


Figure 3.18 The S804 Airfoil.

3.2.3 S805A, S806A, S807, S808 Airfoils

The S805A, S806A, S807 and S808 airfoils belong to another airfoil family characterized by thin tip. It was developed to have a low tip $C_{1,\,max}$ for Reynolds numbers over 1,000,000. It is suitable for stall-regulated blades. It was used by Phoenix Industries for the 7, 9 retrofit blade. Due to the results of 1985 wind tunnel tests, the S805 and S806 were redesigned and replaced by the S805A and S806A airfoils [Tangler, 1995].

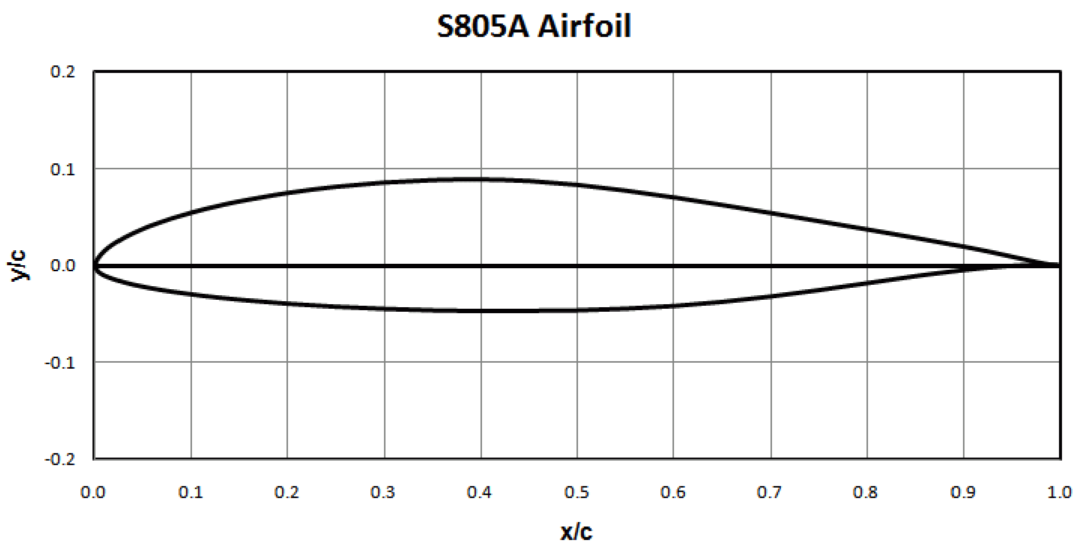


Figure 3.19 The S805A Airfoil.

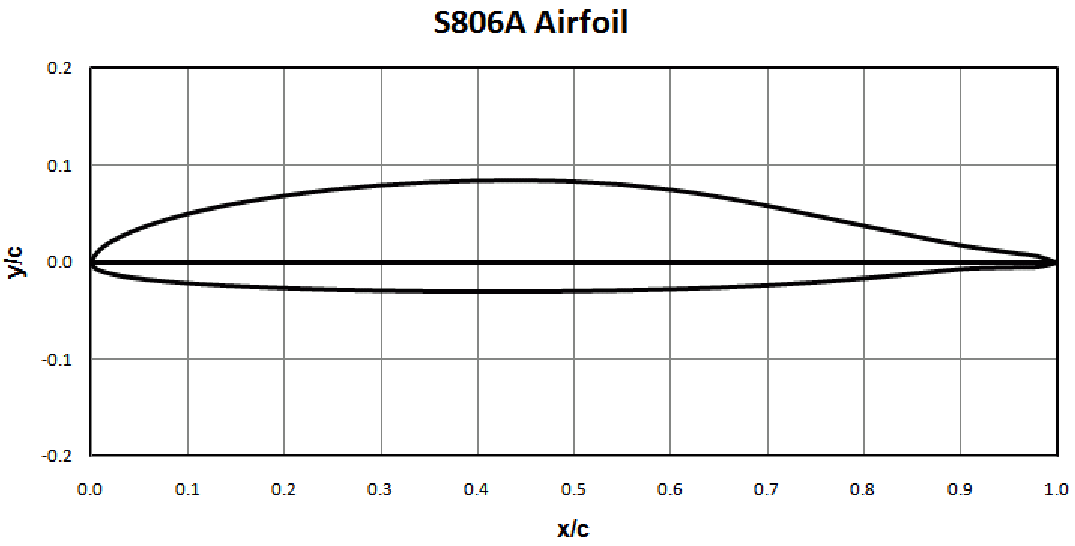


Figure 3.20 The S806A Airfoil.

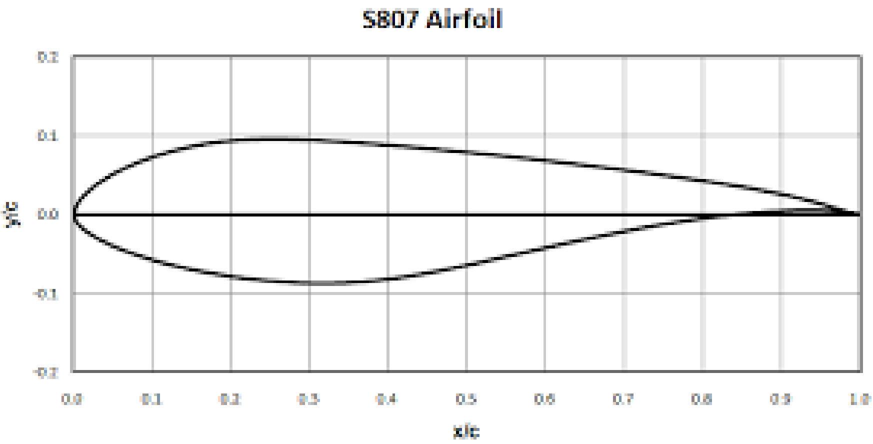


Figure 3.21 The S807 Airfoil.

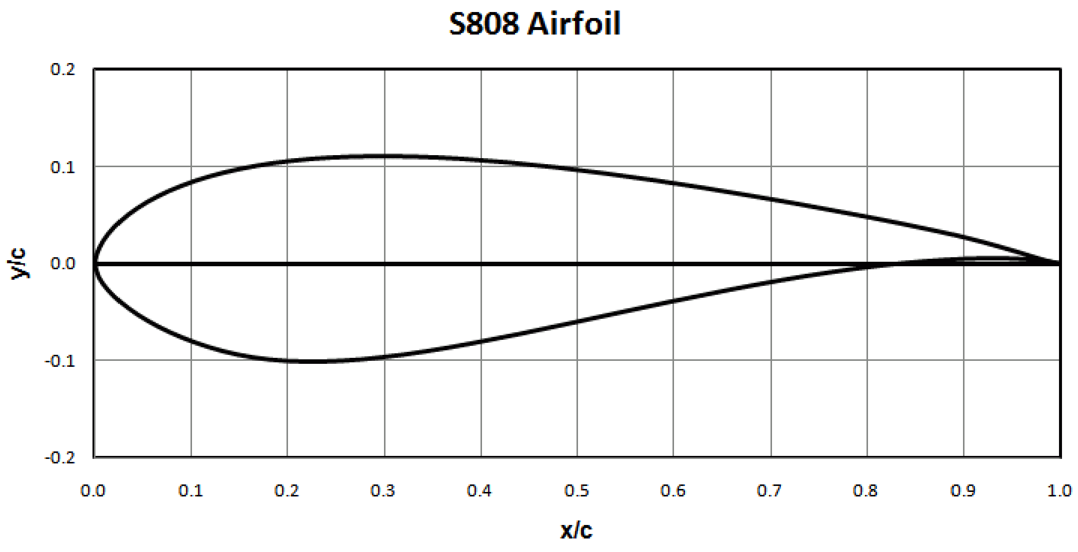


Figure 3.22 The S808 Airfoil.

3.2.4 S819, S820, S821 Airfoils

The primary airfoil of the family is the S819. The S820 is the airfoil of the tip and the S821 is the airfoil of the root. The airfoils S820 and S821 were derived from the airfoil S819 so as to increase the aerodynamic and geometric compatibilities of this category. This category has been designed for 30 to 40 meters, stall-regulated , horizontal-axis wind turbines [Tangler, 1995].

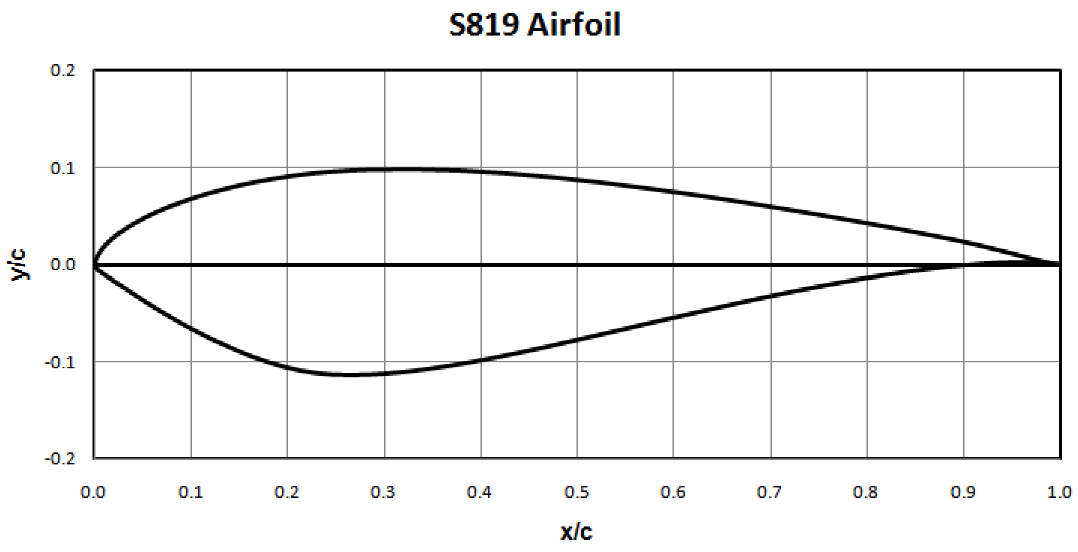


Figure 3.23 The S819 Airfoil.

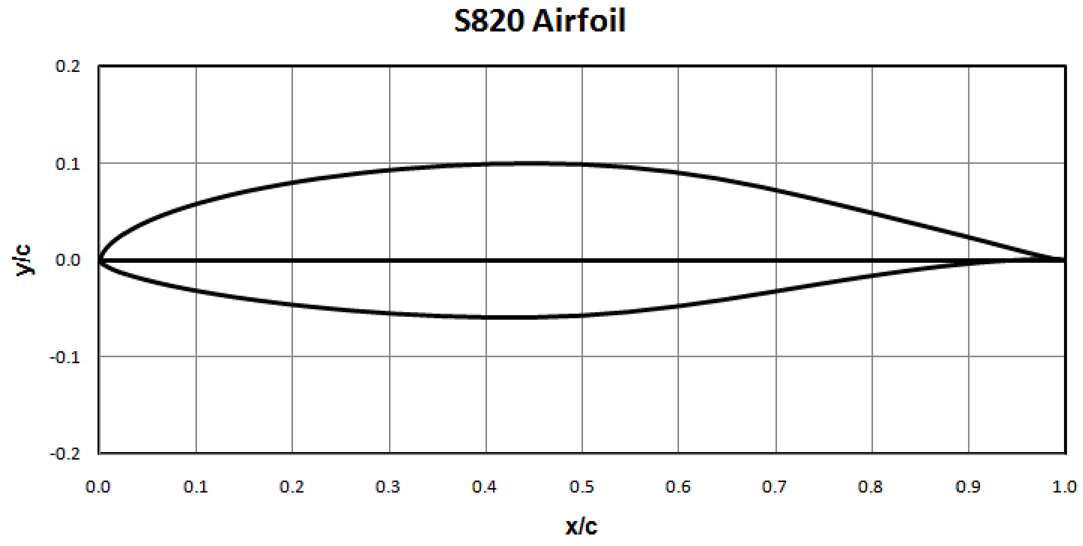


Figure 3.24 The S820 Airfoil.

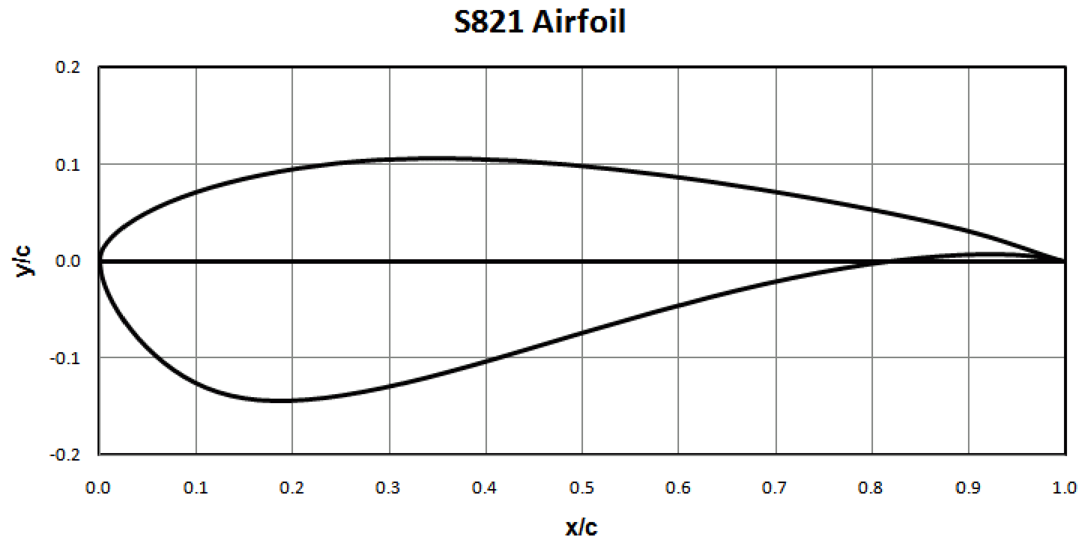


Figure 3.25 The S821 Airfoil.

3.2.5 S809, S810, S814, S815 Airfoils

This airfoil family has been developed for large rotors that are designed for the 100-400 kW range. The primary airfoil is the S809 airfoil. The S811 airfoil but was replaced by S814 and S815. The S814 and the S815 are root airfoils. This airfoil family was developed under the thought of variable rpm rotors that use lightweight blades with low solidity [Tangler, 1995].

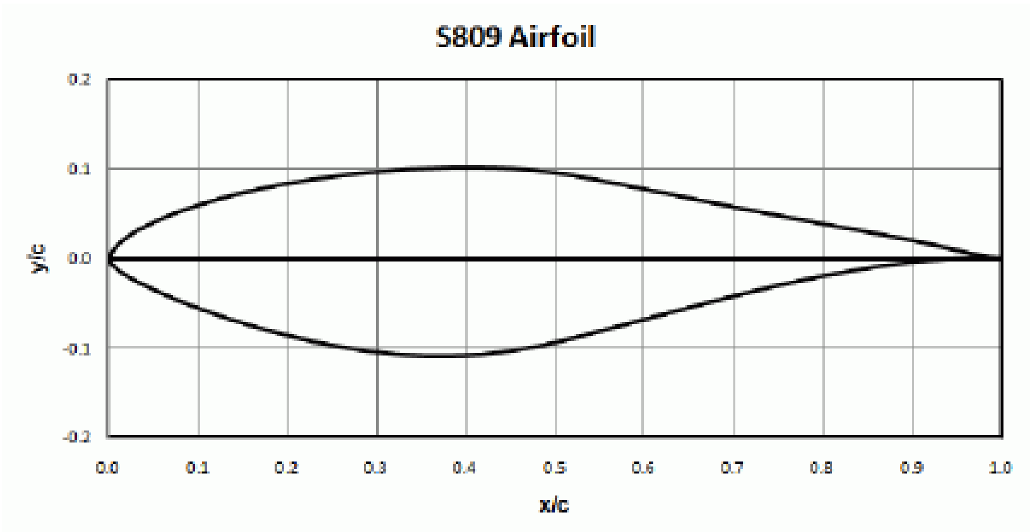


Figure 3.26 The S809 Airfoil.

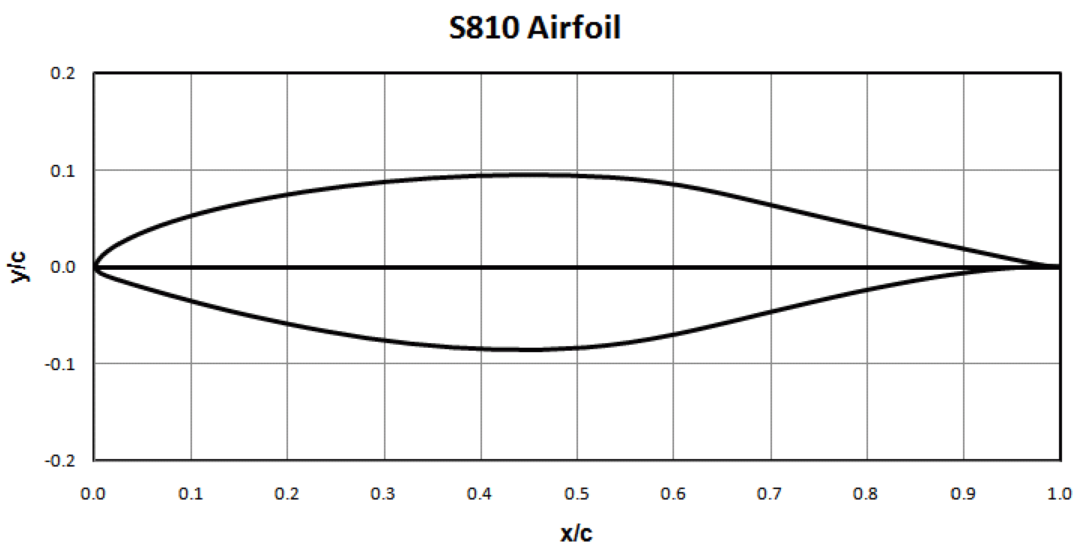


Figure 3.27 The S810 Airfoil.

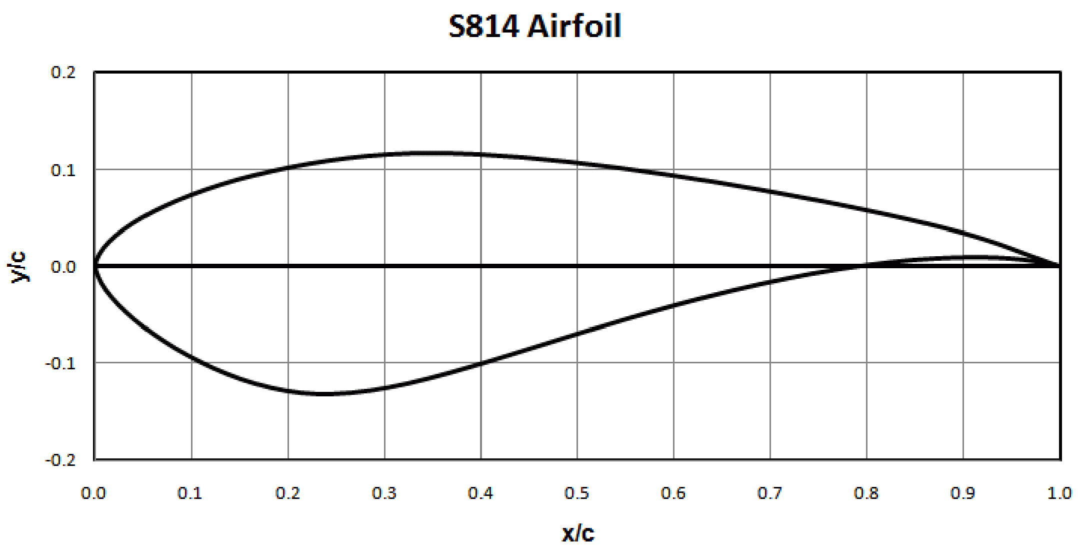


Figure 3.28 The S814 Airfoil.

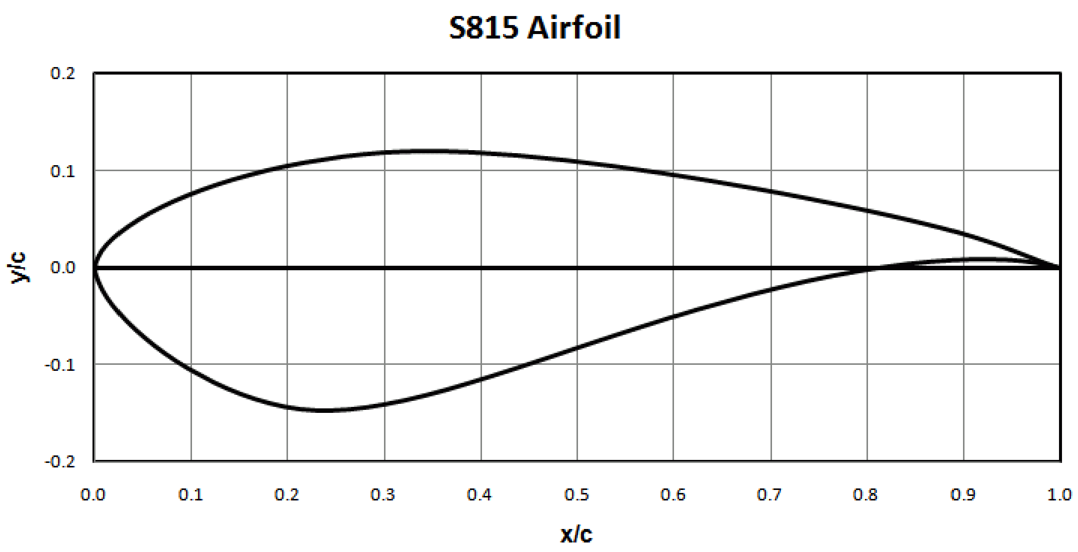


Figure 3.29 The S815 Airfoil.

3.2.6 S812, S813 Airfoils

The S812 and S813 airfoils, are coupled by the most recent airfoils S814 and S815. The S813 airfoil is a tip-region airfoil that has higher $C_{1,\ max}$ and less thickness of 16%. Another airfoil family (S825 and S826) was created in order to be used with the S814 and S815 root airfoils. The airfoil family of S812 and S813 was developed in order to focus on variable-rpm rotors that use lightweight, low solidity blades [Tangler, 1995].

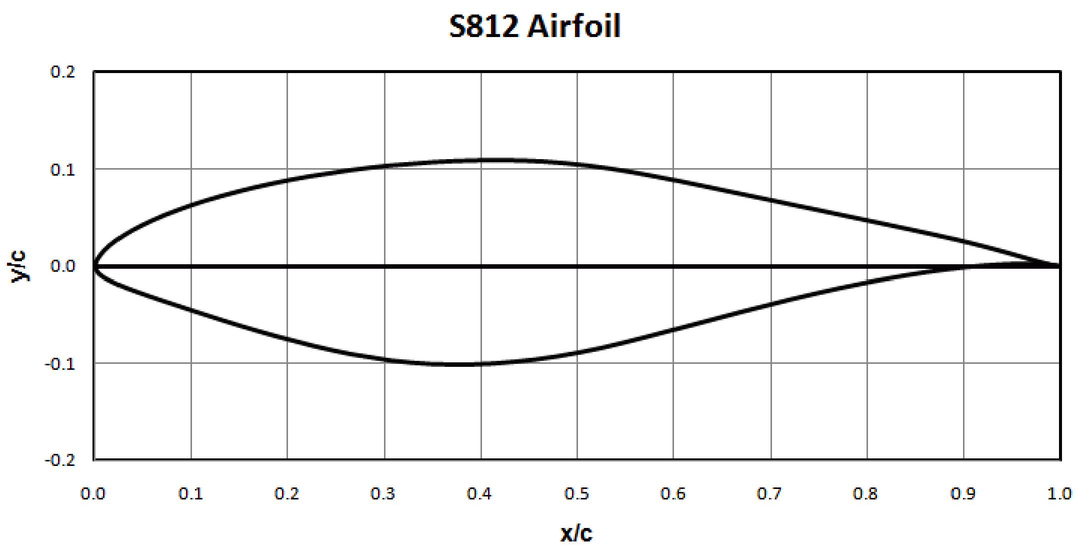


Figure 3.30 The S812 Airfoil.

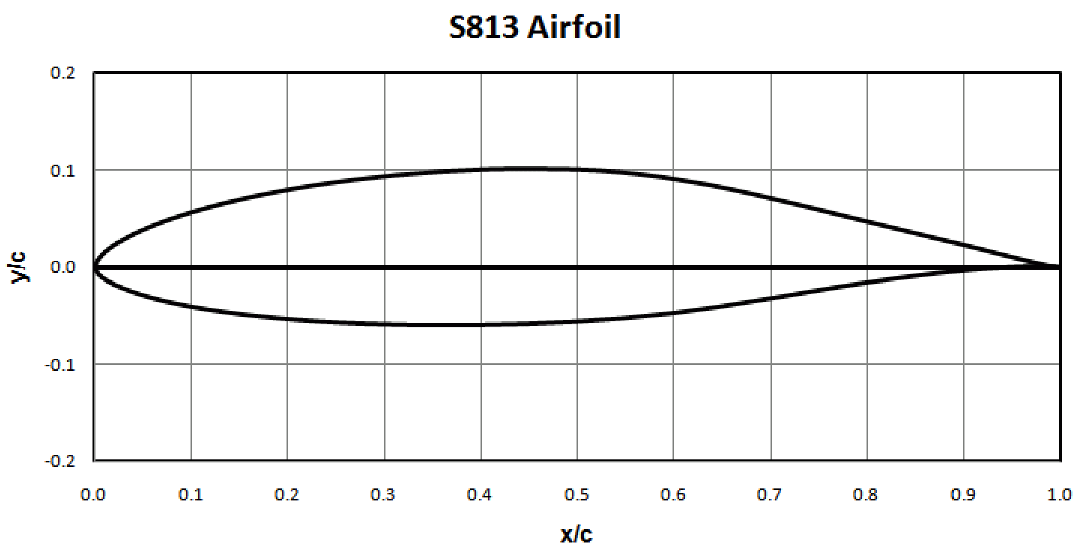


Figure 3.31 The S813 Airfoil.

3.2.7 S816, S817, S818 Airfoils

This airfoil family was created in order to be used in the very large blades that are designed for the 400-1000 kW range. These airfoils are developed for stall-regulated rotors. The tip-region airfoil has a $C_{1,\ max}$ of 1.1 and a thickness of 16%. These airfoils are used on the Zone 500 kW three-bladed wind turbine. This set of airfoils allow the use of more swept area for a given generator size [Tangler, 1995].

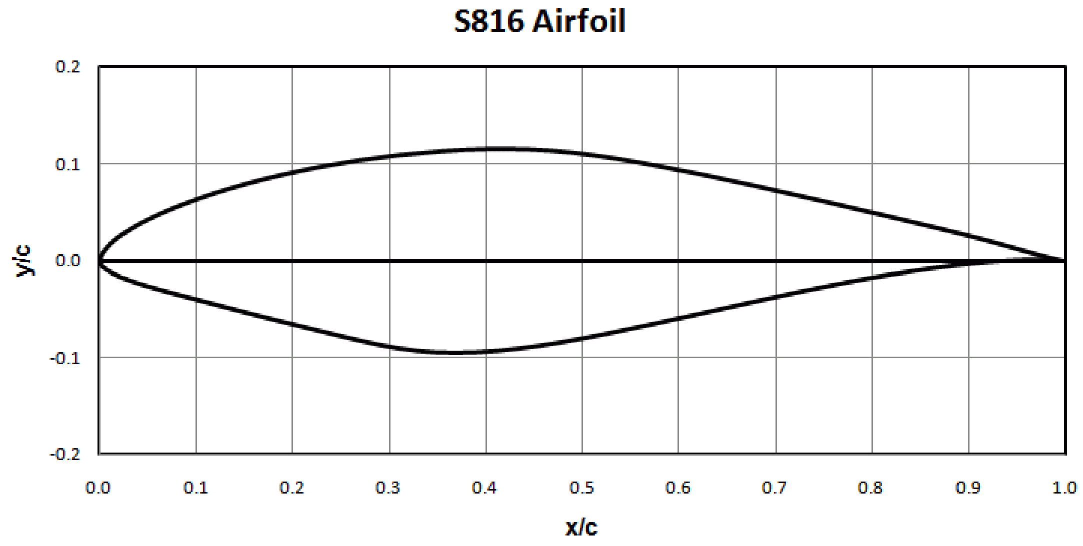


Figure 3.32 The S816 Airfoil.

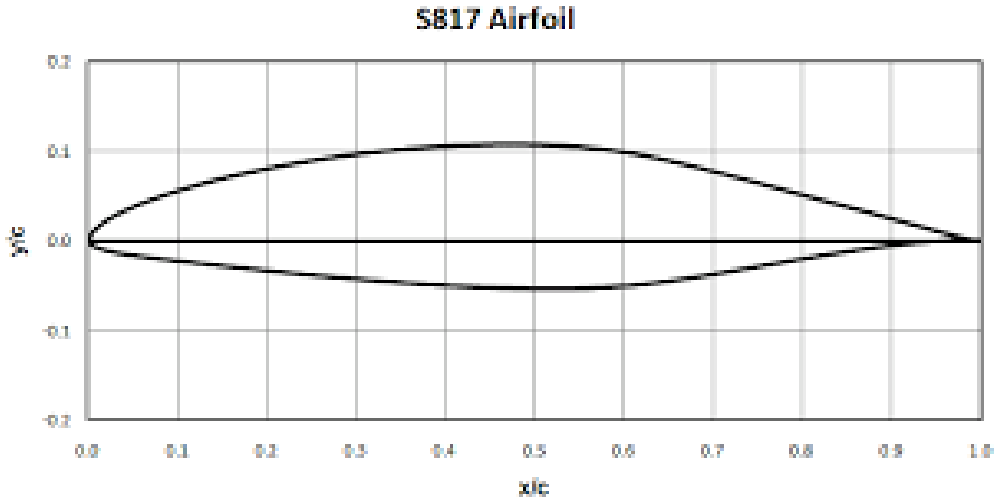


Figure 3.33 The S817 Airfoil.

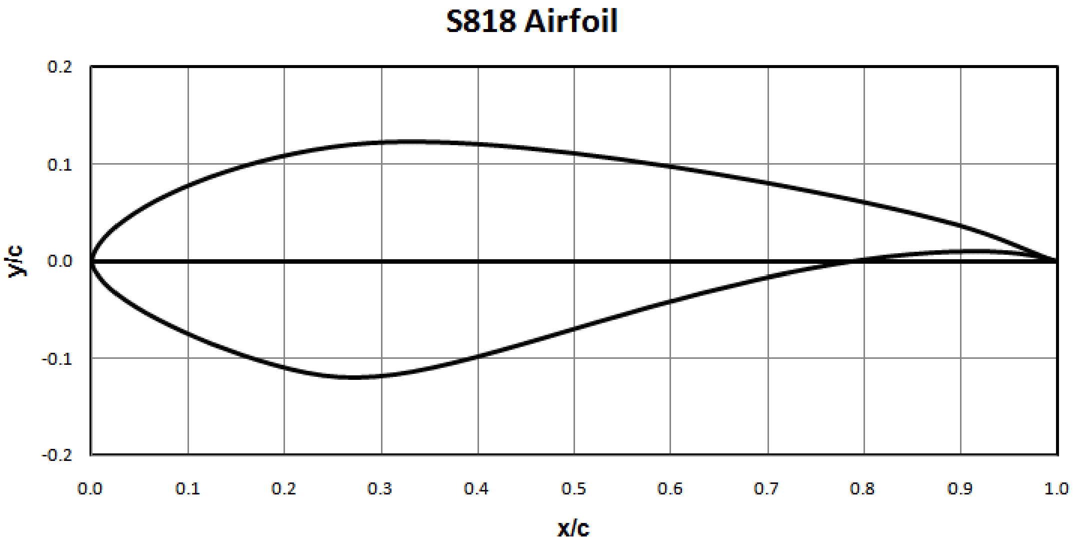


Figure 3.34 The S818 Airfoil.

3.3 RISO Airfoil Families

During the middle of the 1990's, the RISO National Laboratory in Denmark has developed three airfoil families: RISO A1, RISO P and RISO B1 airfoil families. The XFOIL code was the design tool, which was developed by Professor Mark Drela in MIT.

The RISO A1 family was designed in 1990 and was put used for the design of stall-controlled wind turbines. Unfortunately, the sensitivity for the surface roughness was higher than the expected one and the design was completed in 1998. It consists of six airfoils with thickness-to-chord ratio ranging from 15% to 30%. The wind turbine's rated power was around 600 kW.

The RISO P family was developed in 2001 and consists of 4 airfoils with thickness-to-chord ratios 15 %, 18 %, 21 %, and 24 % for variable-pitch with fixed-speed or variable-speed.

The RISO B1 family was designed as seven separate airfoils with thickness-to-chord ratios ranging from 15% to 53%. This airfoil family was designed for MW-sized wind turbines, with variable-speed and pitch control, in order to have maximum lift and high design-lift [Mamadaminov, 2013].

RISO airfoils were tested in the VELUX wind tunnel, which has an open test section with a turbulence background of 1%. The highest carried Reynolds number was $1.6x10^6$ [Bertagnolio, 2001].

3.3.1 RISO-A Airfoils

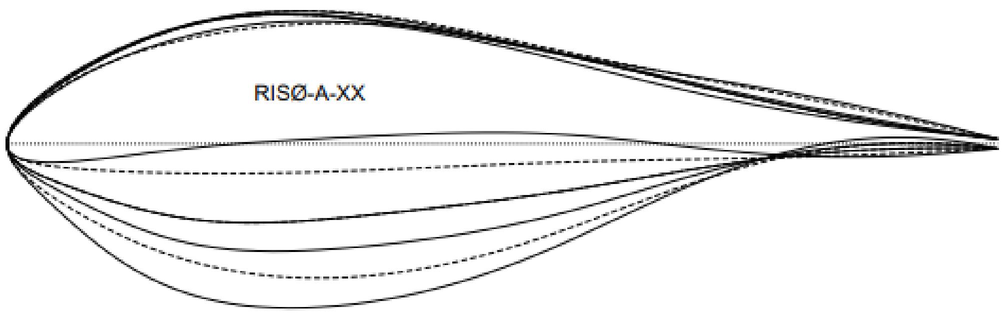


Figure 3.35 The RISO-A-XX Airfoils.

Geometrically, RISO-A-18 to RISO-A-30 are clearly a family. Instead, the airfoil RISO -A-12 & -A-15 are not like their relatives. The entire family is characterized by a sharp leading edge [Dahl, 1998].The airfoils RISO-A-27 and RISO-A-30 have slightly wavy rear part. It might be possible to remove if not for anything else but for aesthetic reasons without compromising the aerodynamic performance [Dahl, 1998]. The Riso-A1 airfoil family was developed for rotors rated at 600 kW and more. The wind tunnel test showed that this airfoil family is suitable for stall and active stall control with a moderate $C_{1, max}$ high C_1/C_d ratio in the design point range, and a smooth post-stall region [Fuglsang, 2004b].

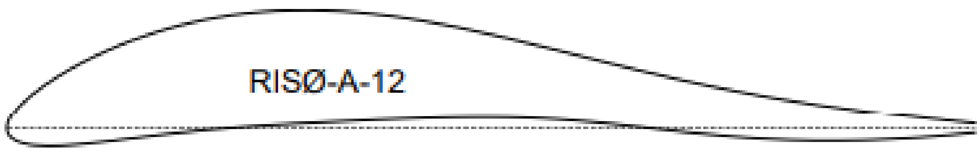


Figure 3.36 The RISO-A-12 Airfoil.

Figure 3.37 The RISO-A-15 Airfoil.

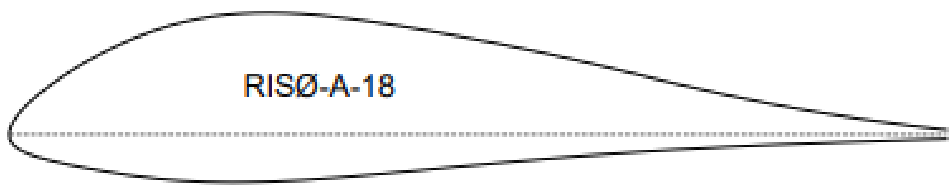


Figure 3.38 The RISO-A-18 Airfoil.

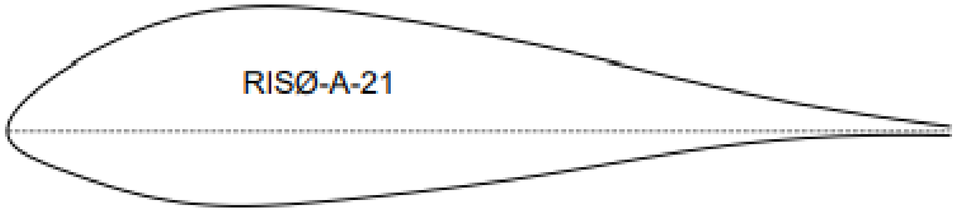


Figure 3.39 The RISO- A-21 Airfoil.

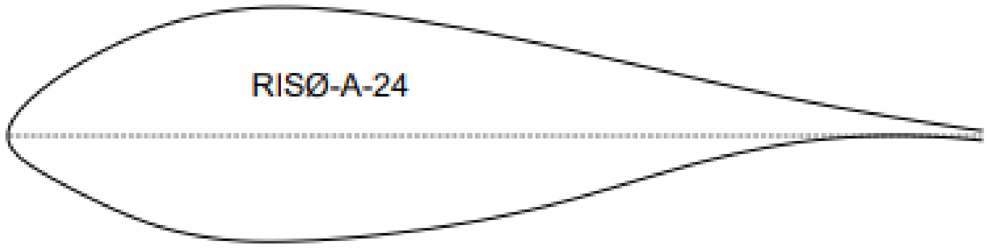


Figure 3.40 The RISO-A-24 Airfoil.

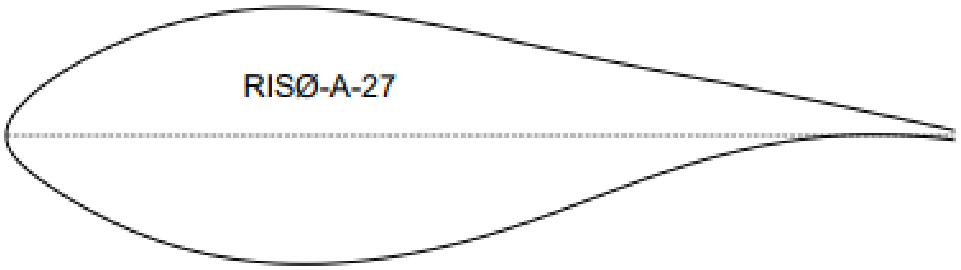


Figure 3.41 The RISO-A-27 Airfoil.

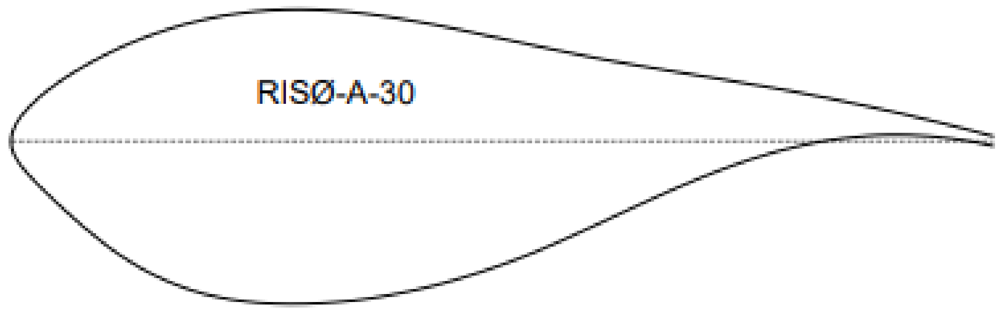


Figure 3.42 The RISO–A-30 Airfoil.

3.3.2 RISO–B1 Airfoils

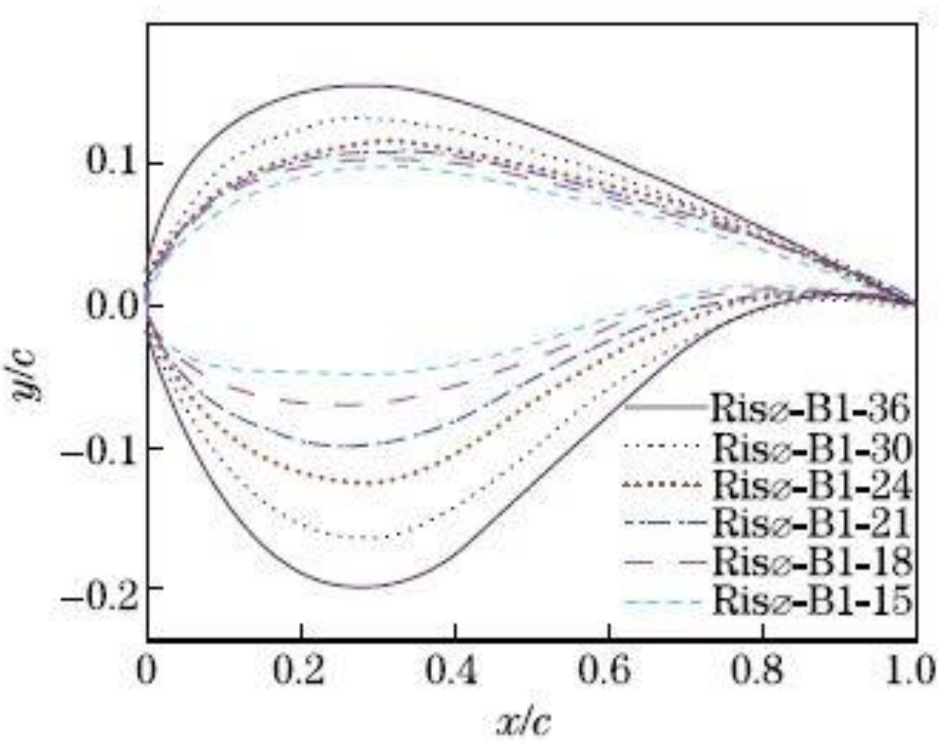


Figure 3.43 The RISO–B1 Airfoil family.

The RISO-B1 Airfoil family was designed for large MW–sized wind turbines, having variable speed and pitch control. The goals of the specific design was: 1) the maximization of the airfoil force coefficient contributing to rotor torque on a wind turbine in a specified design range and 2) a high $C_{1\text{-max}}$ and a high design C_1.The insensitivity of maximum lift to nose roughness was guaranteed by two additional design objectives: 1) Having suction side transition from laminar to turbulent flow in the leading edge region for angles of attack at $C_{1,\,max}$ and 2) obtaining a high $C_{1,max}$ with simulated leading edge roughness. Further design objectives ensured good compatibility between the successive airfoil sections and good geometric properties for inboard airfoil sections [Fuglsang, 2004].

3.3.3 RISO-P Airfoils

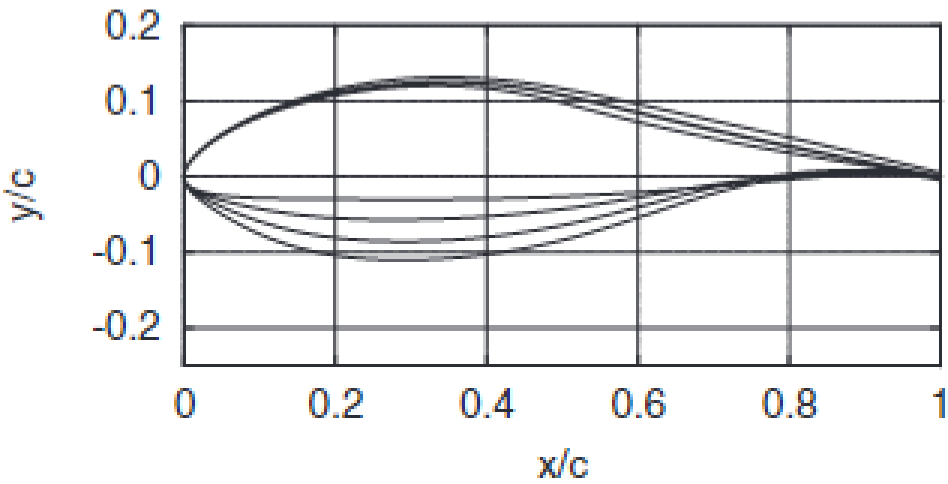


Figure 3.44 The RISO–P Airfoil family.

The RISO-P airfoil family was developed in order to replace the RISO-A1 airfoil family for use on pitch-controlled rotors with fixed or variable speed. This airfoil family was developed in 2001. It includes four airfoils with thickness-to-chord ratios 15 %, 18 %, 21 %, and 24 %. The overall performance should be identical to RISO-A1 family but, because of the improved design objectives, many changes have been done in the leading edge region. Also, a reduction of the sensitivity to roughness was expected [Fuglsang, 2004 b].

3.4 FFA Airfoil Family

Another category of airfoils is the FFA-Series. They produce structurally efficient airfoils with a higher C_1 than the common aviation airfoils. The FFA airfoils were designed specifically for a 45 meter diameter HAWT. That wind turbine operated at constant tip-speed-ratio and controlled by yawing out of wind. The FFA-W1-xxx series was created with this rotor in mind [Bjorck, 1990].

3.4.1 FFA–W1 Series

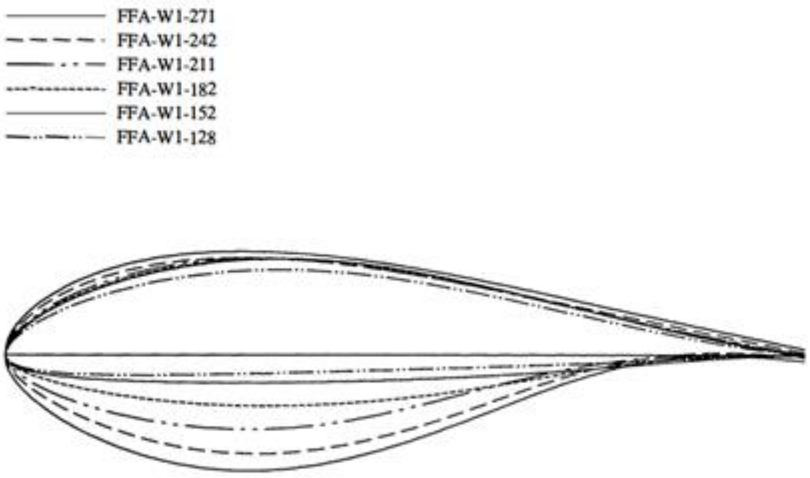


Fig.14 The FFA-W1-xxx airfoils plotted superimposed on each other.

Figure 3.45 FFA-W1-xxx airfoils.

The first series of FFA airfoils have thickness-to-chord ratios spanning from 12.8% up to 27.1%. The design lift coefficients start from 0.9 for the 12.8% airfoil, continues to 1.05 for the 15.2% airfoil, and finally spans to 1.2 for the 27.1% airfoil [Bjorck, 1990].

The FFA-W1 series is developed with better L/D ratio instead of high-lift coefficients. The thickness-to-chord ratio up to 27.1% of the airfoils belongs to this category. The design lift coefficient C_1 has been increased from a value of 1.05 (corresponding to the 15.2% thick section) to a value of 1.2 (corresponding to the 21.1% thick section). For thicker airfoils the design objective is a higher L/D (as possible) with a rough surface.

3.4.2 FFA–W2 Series

The second series of FFA airfoils includes only two airfoils. These are designed with lift coefficients 0.15 units lower than the first series [Bjorck, 1990]. The goal of their creation is to design a different series of airfoils with different C_1, like NACA 6-series. Specifically, the airfoil FFA-W2-152 is designed with lower C_1 than FFA-W1-152 [Bjorck, 1990].

Also, the FFA-W2 series is also designed to have lower $C_{1, max}$ than FFA-W1 series and specifically the airfoil FFA-W2-210 has lower design C_1 and $C_{1, max}$ than the FFA-W1-211 airfoil.

3.4.3 FFA- W3 Series

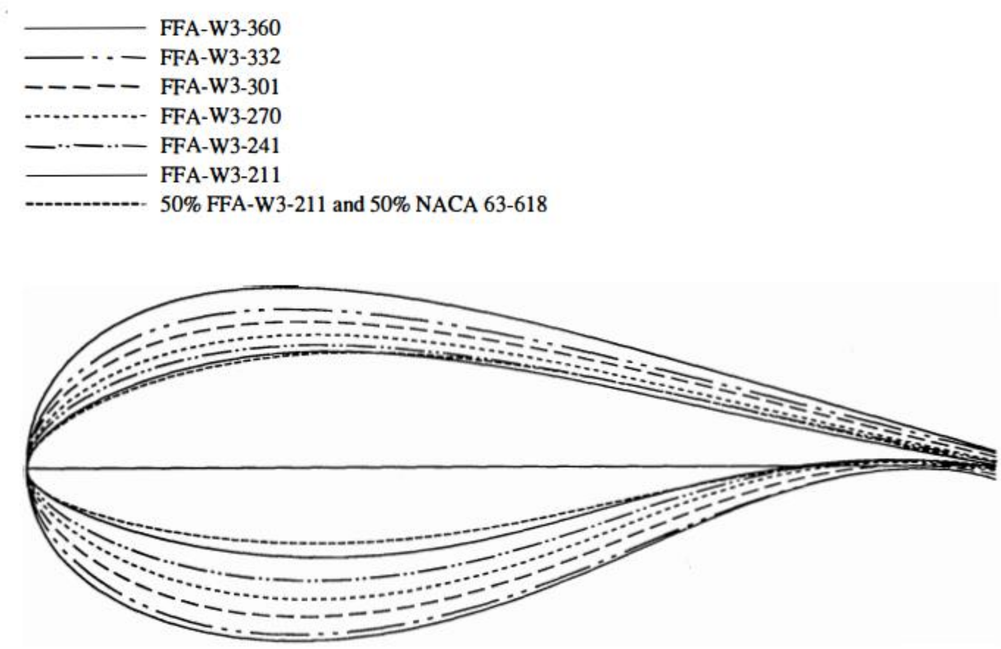


Figure 3.46 The FFA-W3-xxx airfoils.

The third series has airfoils with thickness-to-chord ratios spanning from 19.5% up to 36%. There are two specifically thick airfoils of this series that are designed to follow NACA 63-600 airfoils [Bjorck, 1990].

The airfoil FFA-W1-211 was adapted in order to give better conformity to the thinner NACA 63-618 airfoil, because it was designed for more aft loading. Calculations with XFOIL showed that the FFA-W3-211 gave higher $C_{1, max}$ than the FFA-W1-211. The

FFA-W3 airfoils have slightly more camber than the FFA-W1 airfoils. Also, the FFA-W3 airfoils have slightly larger pitching moment coefficients [Bjorck, 1990].

The airfoils FFA-W3-241 and FFA-W3-301 have been designed at FFA (The Aeronautical Research Institute of Sweden) [Bjorck, 1990]. They are thick and their use is on the inboard part of various wind turbine blades [Bertagnolio, 2001].

3.5 FX66 S196 V1 Airfoil

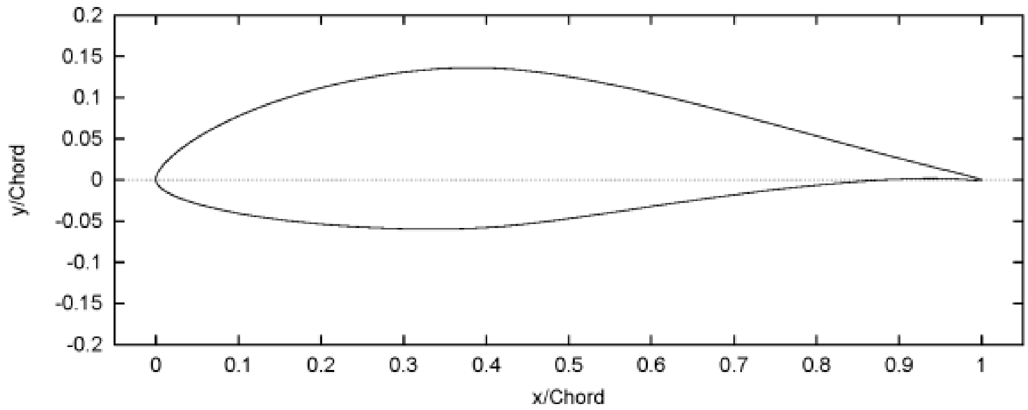


Figure 3.47 The FX66 S196 V1 Airfoil.

The FX66 S196 V1 airfoil is a 19% thick airfoil, which was designed by Althaus and Wortmann at the University of Stuttgart. It is a typical laminar-flow airfoil where the transitional effects are large since the laminar flow is over the majority of the airfoil surface [Bertagnolio, 2001].

In most cases, this airfoil was designed for applications in sailplanes. The characteristic of this airfoil is the wide range of low drag and the high value of the maximum lift coefficient, which are valuable characteristics for a sailplane [Gooden, 1978].

FX66 S196 V1 airfoil was under investigations in order to provide more data for sailplane performance calculation and also for the knowledge about laminar separation bubbles. The airfoil model had a high accuracy and was equipped with a large number of pressure values in order to allow accurate measurements of the pressure distributions [Gooden, 1978].

3.6 DU 91 W2 250 Airfoil and DU 93 W 210 Airfoil

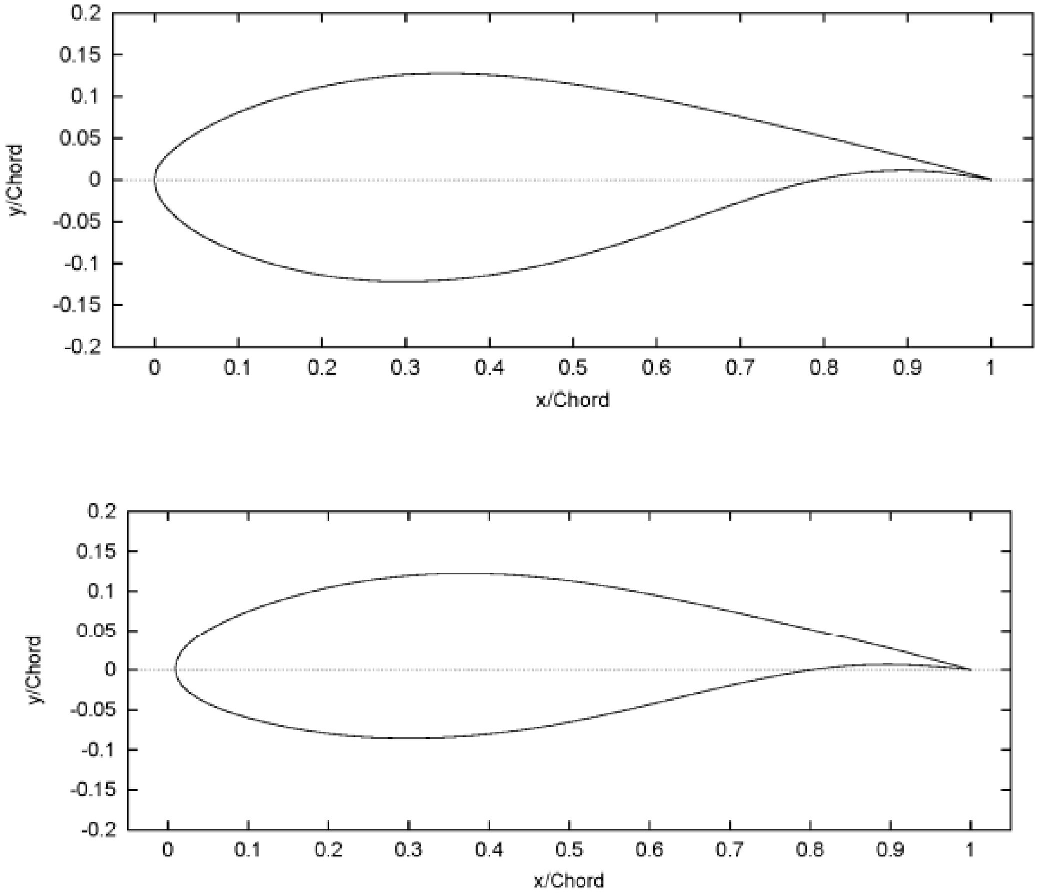


Figure 3.48 The DU-91-W2-250 Z(top) and DU-9- W-210 Airfoils.

In the DU 91-W2-250 (25% thick) airfoil (TU-Delft), the design goal for the laminar case was a peak lift coefficient of 1.5, relatively smooth stall and insensitive to roughness. Furthermore, the DU 91-W2-250 was developed with a trailing edge gap of 0.65% chord [Shuang Li, 2018]. The DU-93-W-210 (21% thick) was designed also at TU Delft [Bertagnolio, 2001].

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