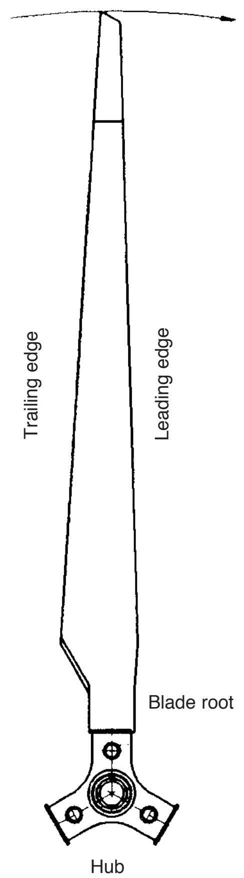
THE AERODYNAMICS OF THE WIND TURBINE

The three bladed rotor is the most important and most visible part of the wind turbine. It is through the rotor that the energy of the wind is transformed into mechanical energy that turns the main shaft of the wind turbine.

We will start by describing why the blades are shaped the way that they are and what really happens, when the blades rotate.

BASIC THEORY

Aerodynamics is the science and study of the physical laws of the behavior of objects in an air flow and the forces that are produced by air flows.



The different components of a wind turbine blade

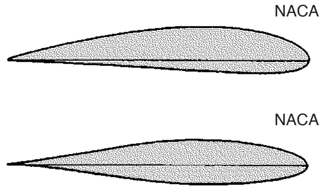
The front and rear sides of a wind turbine rotor blade have a shape roughly similar to that of a long rectangle, with the edges bounded by the leading edge, the trailing edge, the blade tip and the blade root. The blade root is bolted to the hub.

The radius of the blade is the distance from the rotor shaft to the outer edge of the blade tip. Some wind turbine blades have moveable blade tips as air brakes, and one can often see the distinct line separating the blade tip component from the blade itself.

If a blade were sawn in half, one would see that the cross section has a streamlined asymmetrical shape, with the flattest side facing the oncoming air flow or wind. This shape is called the blade's aerodynamic profile

THE AERODYNAMIC PROFILE

The shape of the aerodynamic profile is decisive for blade performance. Even minor alterations in the shape of the profile can greatly alter the power curve and noise level. Therefore a blade designer does not merely sit down and outline the shape when designing a new blade. The shape must be chosen with great care on the basis of past experience. For this reason blade profiles were previously chosen from a widely used catalogue of airfoil profiles developed in wind tunnel research by NACA (The United States National Advisory Committee for Aeronautics) around the time of the Second World War.



Blade profiles

The NACA 44 series profiles were used on older Bonus wind turbines (up to and including the 95 kW models). This profile was developed during the 1930's, and has good all-round properties, giving a good power curve and a good stall. The blade is tolerant of minor surface imperfections, such as dirt on the blade profile surface.

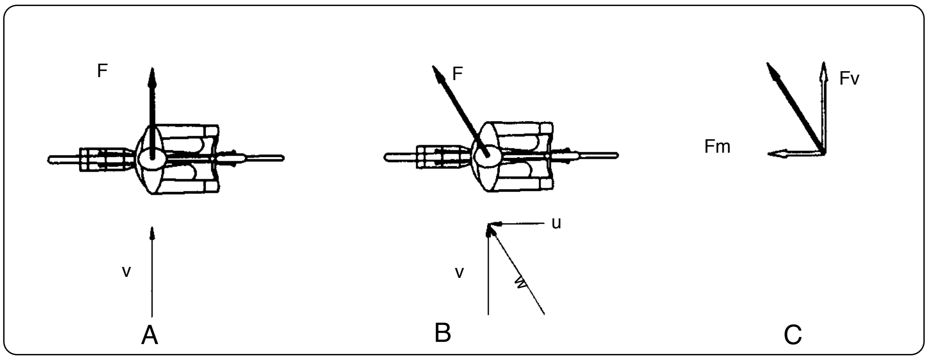
The LM blades used on newer Bonus wind turbines (from the 150 kW models) use the NACA 63 profiles developed during the 1940´s. These have slightly different properties than the NACA 44 series. The power curve is better in the low and medium wind speed ranges, but drops under operation at higher wind speeds. Likewise this profile is more sensitive with regard to surface dirt. This is not so important in Denmark, but in certain climate zones with little rain, accumulated dirt, grime and insect deposits may impair and reduce performance for longer periods.

The LM 19 blades, specifically developed for wind turbines, used on the Bonus 500 kW, have completely new aerodynamic profiles and are therefore not found in the NACA catalogue. These blades were developed in a joint LM and Bonus research project some years ago, and further developed and wind tunnel tested by FFA (The Aerodynamic Research Institute of The Swedish Ministry of Defence).

THE AERODYNAMICS OF A MAN ON A BICYCLE

To fully describe the aerodynamics of a wind turbine blade could appear to be rather complicated and difficult to understand. It is not easy to fully understand how the direction of the air flow around the blade is dependent on the rotation of the blade. Fortunately for us, air constantly flows around everyday objects following these very same aerodynamic laws. Therefore we can start with the aerodynamics of an air flow that most of us are much more familiar with: A cyclist on a windy day.

The diagrams (next page) show a cyclist as seen from above. The diagrams are perhaps rather sketchy, but with a good will one can visualize what they

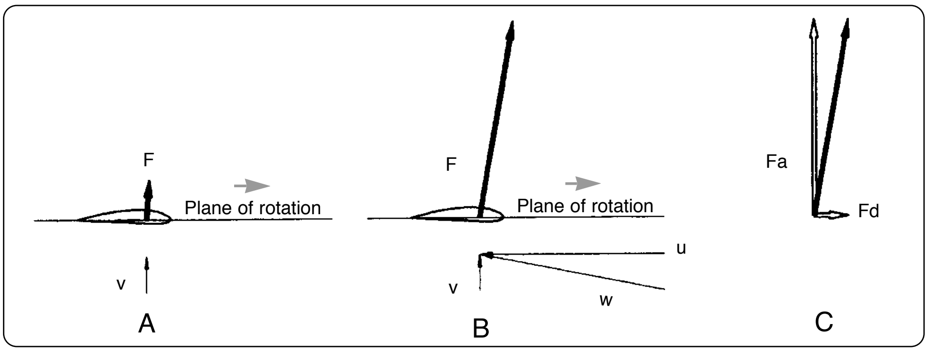


Air flow around a man on a bicycle

represent. The diagram (A) on the left, illustrates a situation, during which a cyclist is stationary and can feel a side wind "v" of 10 meters per second (m/s) or roughly 22 mph (this is known as a fresh breeze). The wind pressure will attempt to overturn the cyclist. We can calculate the pressure of the wind on the windward side of the cyclist as roughly 80 Newton per square meter of the total side area presented by the cyclist against the wind. Newton, or N for short, is the unit for force used in technical calculation. 10 N is about 1kg/force (Multiply by 0.2248 to obtain lbf.). The direction of the force of the wind pressure is in line with the wind flow. If we consider that a normal sized cyclist has a side area facing the wind of about 0.6 square meters, then the force F from the pressure of the wind will be 0.6 x 80 N = app. 50 N/m^2.

In the center drawing (B) our cyclist has started out and is traveling at a speed "u" of 20 km/hour, equivalent to about 6 meters/second, still with a side wind "v" of 10 m/s. We can therefore calculate the speed of the resulting wind "w" striking the cyclist, either mathematically or by measurement on the diagram as 12 m/s. This gives a total wind pressure of 100 N/m^2. The direction of the wind pressure is now in line with the resulting wind, and this will give a force "F" on the cyclist of about 60 N/m^2.

In the right hand drawing (C) the force of the wind pressure "F" is now separated into a component along the direction of the cyclist's travel and into another component at a right angle to the direction of travel. The right angled force "Fv" will attempt to overturn the cyclist, and the force "Fm" along the axis of travel gives a resistance that slows down the cyclist's forward motion. The size of "Fm" is about 30 N/m^2. This is the resistance force that the cyclist must overcome. A beginner, unused to cycling, may wonder why the wind has changed direction and a head wind is felt on reaching speed. This beginner might well ask " How can it be that I felt a side wind when I was at rest and standing still, could the wind have possibly changed its direction? " But no, as any experienced cyclist unfortunately knows, head wind is an integral component of movement itself. The wind itself has not turned. The head wind is a result of speed, the faster one travels the more wind resistance one experiences. Perhaps, as a famous Danish politician once promised his voters, that if elected he would insure favorable tailwinds on the cycle-paths, things may change in the future. However we others have learnt to live with the head winds resulting from our own forward movement, whether we run, cycle or go skiing.



Airflow around a blade profile, near the wing tip

WIND TURBINE BLADES BEHAVE IN THE SAME WAY

Returning to the wind turbine blade, just as in the situation for the cyclist, we can observe the aerodynamic and force diagrams in two different situations, when the wind turbine is stationary and when it is running at a normal operational speed. We will use as an example the cross section near the blade tip of a Bonus 450 kW Mk III operating in a wind speed "v" of 10 m/s.

When the rotor is stationary, as shown in drawing (A) below, the wind has a direction towards the blade, at a right angle to the plane of rotation, which is the area swept by the rotor during the rotation of the blades. The wind speed of 10 m/s will produce a wind pressure of 80 N/m^2 of blade surface, just like the effect on our cyclist. The wind pressure is roughly in the same direction as the wind and is also roughly perpendicular to the flat side of the blade profile. The part of the wind pressure blowing in the direction of the rotor shaft attempts to bend the blades and tower, while the smaller part of the wind pressure blowing in the direction of the rotation of the blades produces a torque that attempts to start the wind turbine.

Once the turbine is in operation and the rotor is turning, as is shown in the center diagram (B), the blade encounters a head wind from its own forward movement in exactly the same way as the cyclist does. The strength of head wind "u" at any specific place on the blade depends partly on just how fast the wind turbine blade is rotating, and partly how far out on the blade one is from the shaft. In our example, at the normal operating speed of 30 rpm, the head wind "u" near the tip of the 450 kW wind turbine is about 50 m/s. The "meteorological" wind "v" of 10 m/s will thus give a resulting wind over the profile of about 51 m/s.

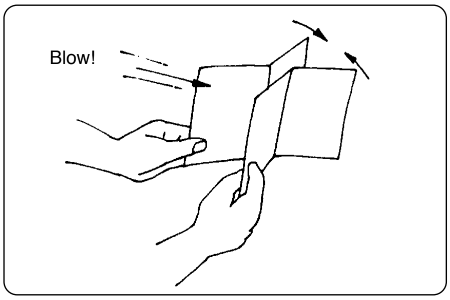
This resulting wind will have an effect on the blade surface with a force of 1500 N/m^2. The force "F" will not be in the direction of the resulting wind, but almost at a right angle to the resulting wind.

In the drawing on the right (C) the force of the wind pressure "F" is again split up into a component in the direction of rotation and another component at a right angle to this direction. The force "Fa" at a right angle to the plane of rotation attempts to bend the blade back against the tower, while the force "Fd" points in the direction of rotation and provides the driving torque. We may notice two very important differences between the forces on the blade in these two different situations and forces on the cyclist in the two corresponding situations. One difference is that the forces on the blade become very large during rotation. If vector arrows illustrating the forces in the diagrams were drawn in a scale that was indicative of the sizes of the different forces, then these vector arrows of a wind turbine in operation would have been 20 times the size of the vector arrows of the same wind turbine at rest. This large difference is due to the resulting wind speed of 51 m/s striking a blade during operation, many times the wind speed of 10 m/s when the wind turbine is at rest. Just like the cyclist, the blade encounters head wind resulting from its own movement, however head wind is of far greater importance on a wind turbine blade than for a cyclist in motion.

The other important difference between a wind turbine blade and a cyclist is that the force on the blade is almost at a right angle to the resulting wind striking the profile. This force is known as the lift and also produces a small resistance or drag. The direction of this lift force is of great importance. A cyclist only feels the wind resistance as a burden, requiring him to push down extra hard on the pedals. However with a wind turbine blade this extra wind resistance will act as a kind of power booster, at least in the normal blade rotational speed range. The reason for this difference is due to the blades streamlined profile, which behaves aerodynamically completely differently as compared to the irregular shaped profile of a man on a bicycle. The wind turbine blade experiences both lift and drag, while a cyclist only experiences drag.

LIFT

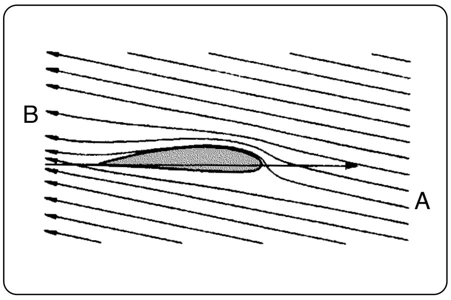
Lift is primary due to the physical phenomena known as Bernoulli's Law. This physical law states that when the speed of an air flow over a surface is increased the pressure will then drop. This law is counter to what most people experience from walking or cycling in a head wind, where normally one feels that the pressure increases when the wind also increases. This is also true when one sees an air flow blowing directly against a surface, but it is not the case when air is flowing over a surface.



An experiment with Bernoulli's Law

One can easily convince oneself that this is so by making a small experiment. Take two small pieces of paper and bend them slightly in the middle. Then hold them as shown in the diagram and blow in between them. The speed of the air is higher in between these two pieces of paper than outside (where of course the air speed is about zero), so therefore the pressure inside is lower and according to Bernoulli's Law the papers will be sucked in towards each other. One would expect that they would be blown away from each other, but in reality the opposite occurs. This is an interesting little experiment, that clearly demonstrates a physical phenomenon that has a completely different result than what one would expect. Just try for yourself and see.

The aerodynamic profile is formed with a rear side, that is much more curved than the front side facing the wind. Two portions of air molecules side by side in the air flow moving towards the profile at point A will separate and pass around the profile and will once again be side by side at point B after passing the profile's trailing edge. As the rear side is more curved than the front side on a wind turbine blade, this means that the air flowing over the rear side has to travel a longer distance from point A to B than the air flowing over the front side. Therefore this air flow over the rear side must have a higher velocity if these two different portions of air shall be reunited at point B. Greater velocity produces a pressure drop on the rear side of the blade, and it is this pressure drop that produces the lift. The highest speed is obtained at the rounded front edge of the blade. The blade is almost sucked forward by the pressure drop resulting from this greater front edge speed.



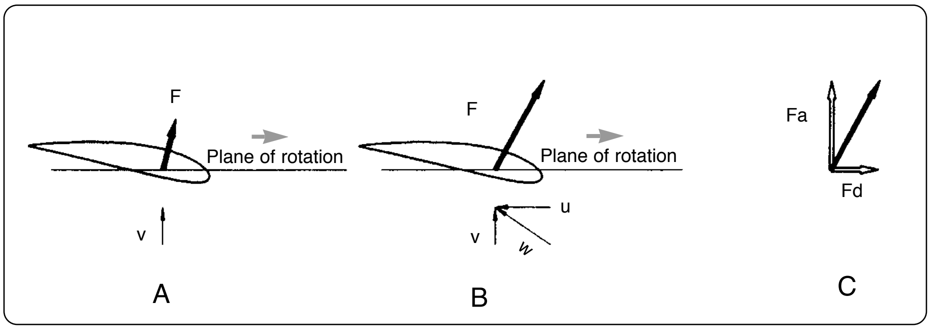
Air flow around an aerodynamic profile

There is also a contribution resulting from a small over-pressure on the front side of the blade.

Compared to an idling blade the aerodynamic forces on the blade under operational conditions are very large. Most wind turbine owners have surely noticed these forces during a start-up in good wind conditions. The wind turbine will start to rotate very slowly at first, but as it gathers speed it begins to accelerate faster and faster. The change from slow to fast acceleration is a sign that the blade's aerodynamic shape comes into play, and that the lift greatly increases when the blade meets the head wind of its own movement. The fast acceleration, near the wind turbine's operational rotational speed places great demands on the electrical cut-in system that must "capture and engage " the wind turbine without releasing excessive peak electrical loads to the grid.

THE CHANGE OF FORCES ALONG THE BLADE

The drawings previously studied, mainly illustrate the air flow situation near the



Air flow around a blade profile near the blade root

blade tip. In principle these same conditions apply all over the blade, however the size of the forces and their direction change according to their distance to the tip. If we once again look at a 450 kW blade in a wind speed of 10 m/s, but this time study the situation near the blade root, we will obtain slightly different results as shown in the drawing above.

In the stationary situation (A) in the left hand drawing, wind pressure is still 80 N/m^2. The force "F" becomes slightly larger than the force at the tip, as the blade is wider at the root. The pressure is once again roughly at a right angle to the flat side of the blade profile, and as the blade is more twisted at the root, more of the force will be directed in the direction of rotation, than was the case at the tip.

On the other hand the force at the root has not so great a torque-arm effect in relation to the rotor axis and therefore it will contribute about the same force to the starting torque as the force at the tip.

During the operational situation as shown in the center drawing (B), the wind approaching the profile is once again the sum of the free wind "v" of 10 m/s and the head wind "u" from the blade rotational movement through the air. The head wind near the blade root of a 450 kW wind turbine is about 15 m/s and this produces a resulting wind "w" over the profile of 19 m/s. This resulting wind will act on the blade section with a force of about 500 N/m^2.

In the drawing on the right (C) force is broken down into wind pressure against the tower "Fa", and the blade driving force "Fd" in the direction of rotation.

In comparison with the blade tip the root section produces less aerodynamic forces during operation, however more of these forces are aligned in the correct direction, that is, in the direction of rotation. The change of the size and direction of these forces from the tip in towards the root, determine the form and shape of the blade.

Head wind is not so strong at the blade root, so therefore the pressure is likewise not so high and the blade must be made wider in order that the forces should be large enough. The resulting wind has a greater angle in relation to the plane of rotation at the root, so the blade must likewise have a greater angle of twist at the root.

It is important that the sections of the blade near the hub are able to resist forces and stresses from the rest of the blade. Therefore the root profile is both thick and wide, partly because the thick broad profile gives a strong and rigid blade and partly because greater width, as previously mentioned, is necessary on account of the resulting lower wind speed across the blade. On the other hand, the aerodynamic behavior of a thick profile is not so effective. Further out along the blade, the profile must be made thinner in order to produce acceptable aerodynamic properties, and therefore the shape of the profile at any given place on the blade is a compromise between the desire for strength (the thick wide profile) and the desire for good aerodynamic properties (the thin profile) with the need to avoid high aerodynamic stresses (the narrow profile).

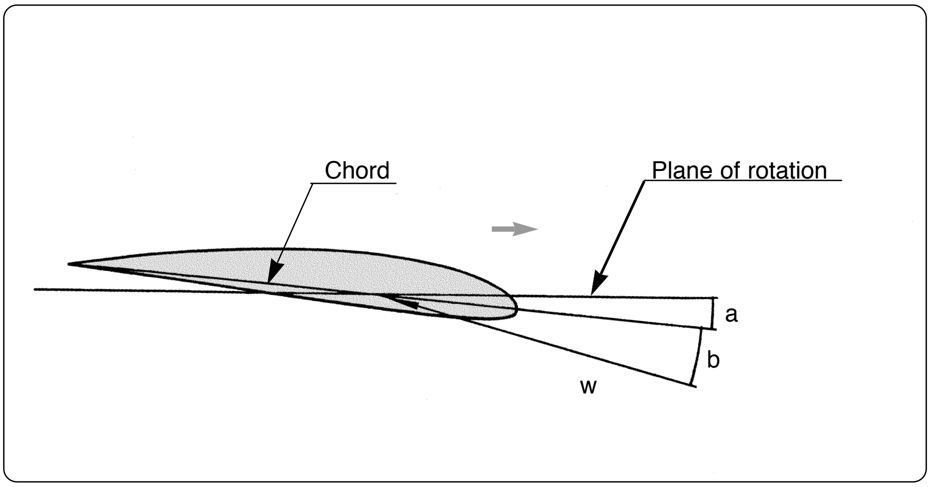
As previously mentioned, the blade is twisted so that it may follow the change in direction of the resulting wind. The angle between the plane of rotation and the profile chord, an imaginary line drawn between the leading edge and the trailing edge, is called the setting angle, sometimes referred to as "Pitch".

WHAT HAPPENS WHEN THE WIND SPEED CHANGES?

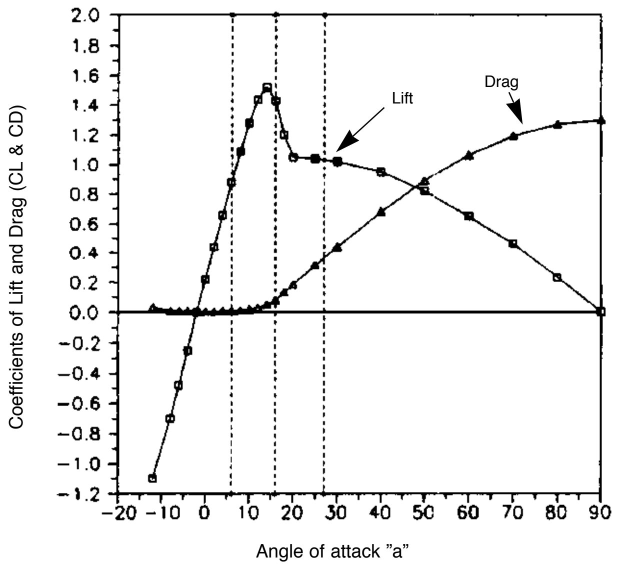
The description so far was made with reference to a couple of examples where wind speed was at a constant 10 m/s. We will now examine what happens during alterations in the wind speed.

In order to understand blade behavior at different wind speeds, it is necessary to understand a little about how lift and drag change with a different angle of attack. This is the angle between the resulting wind "w" and the profile chord. In the drawing below the angle of attack is called "a" and the setting angle is called "b".

The setting angle has a fixed value at any one given place on the blade, but the angle of attack will grow as the wind speed increases.



The angles of the profile



Relationship between lift and drag coefficients and the angle of attack

The aerodynamic properties of the profile will change when the angle of attack "a" changes. These changes of lift and drag with increasing angles of attack, are illustrated in the diagram above used to calculate the strength of these two forces, the lift coefficient "CL" and the drag coefficient "CD". Lift will always be at a right angle to the resulting wind, while drag will always follow in the direction of the resulting wind.

We will not enter into the formulas necessary to calculate these forces, it is enough to know that there is a direct connection between the size of "CL" and the amount of lift.

Both lift and drag abruptly change when the angle of attack exceeds 15-20 degrees. One can say that the profile stalls. After this stalling point is reached, lift falls and drag increases. The angle of attack changes when the wind speed changes.

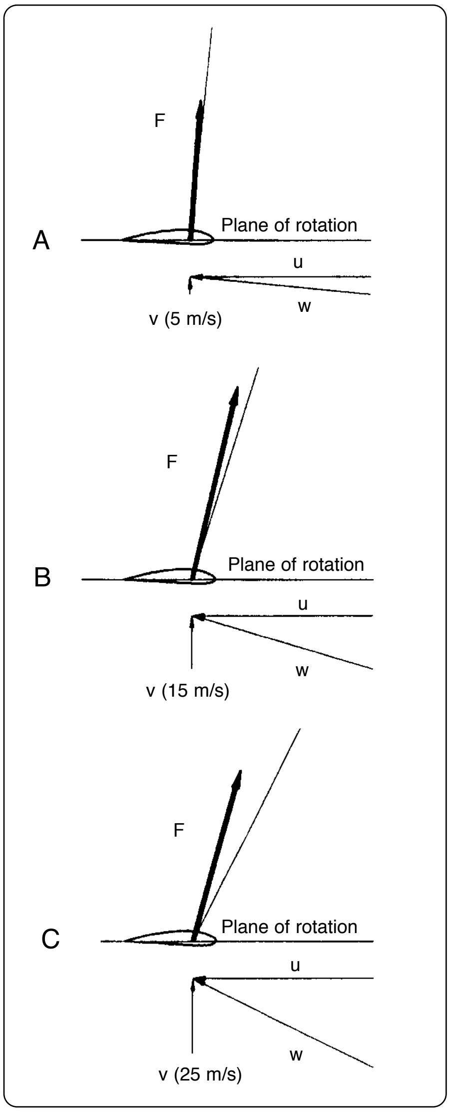
To further study these changes, we can draw diagrams, shown to the right, illustrating three different wind speeds "v" (5, 15 and 25 m/s) from our previous cross section, this time near the blade tip of a 450 kW wind turbine. This situation is rather convenient as the setting angle "b" near the wing tip is normally 0 degrees.

The head wind from the movement "u" is always the same, as the wind turbine has a constant rotational speed controlled by the grid connected generator (in these situations we do not consider the small generator used on certain small wind turbines). The free air flow "v" has three different values and this gives three different values of the resulting wind "w" across the profile. The size of "w" does not change very much, from 50 m/s at a wind speed of 5 m/s to 52 m/s in a 25 m/s wind. The reason for this relatively minor change is due to the dominating effect of the head wind.

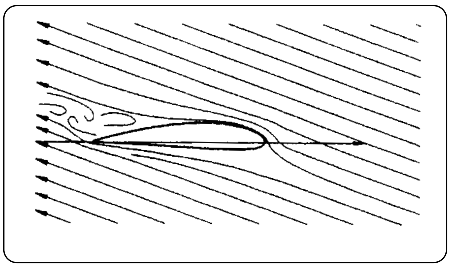
However, the angle of attack "a" between the resulting wind and the chord of the blade changes from 6 degrees at a wind speed of 5 m/s to 16 degrees at 15 m/s to 27 degrees at 25 m/s. These changes are of great importance for determining the strength of the aerodynamic forces.

Studying the diagram showing the lift coefficient "CL" and the drag coefficient "CD" we may note the following:

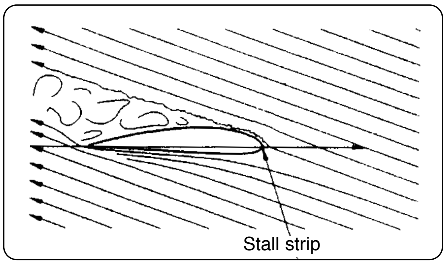
- At a wind speed of 5 m/s (A), the angle of attack is 6 degrees. The lift coefficient is 0.9 and the coefficient of drag is 0.01. Lift is therefore 90 times greater than drag, and the resultant force "F" points almost vertically at a right angle to the mean relative wind "w".
- At a wind speed of 15 m/s (B), the profile is almost about to stall. The angle of attack is 16 degrees. The lift coefficient is 1.4 and the coefficient of drag is 0.07. Lift is now 20 times drag.
- At a wind speed of 25 m/s (C), the profile is now deeply stalled, the angle of attack is 27 degrees, the lift component is 1.0 and the component of lift is 0.35. Lift is now 3 times greater than drag. We can therefore note the following:
- During the change of wind speed from 5 to 15 m/s there is a significant increase in lift, and this increase is directed in the direction of rotation. Therefore power output of the wind turbine is greatly increased from 15 kW to 475 kW.
- During the change of wind speed from 15 to 25 m/s, there is a drop in lift accompanied by an increase in drag. This lift is even more directed in the direction of rotation, but it is opposed by drag and therefore output will fall slightly to 425 kW.



Situations at three different wind speeds



Seperation of the air flow at the profile trailing edge



Interference in the stall process (stall strip)

THE STALL PHENOMENA

The diagrams showing the components of lift and drag illustrate the result of stall. Lift diminishes and drag increases at angles of attack over 15 degrees. The diagrams however do not illustrate the reasons for this stall phenomena.

A stall is understood as a situation during which an angle of attack becomes so large that the air flow no can longer flow smoothly, or laminar, across the profile. Air looses contact with the rear side of the blade, and strong turbulence occurs. This separation of air masses normally commences progressively from the trailing edge, so the profile gradually becomes semi-stalled at a certain angle of attack, but a full stall is first achieved at a somewhat higher angle. From the diagram showing the lift and drag components, one can estimate that the separation at the trailing edge starts at about 12 degrees, where the curve illustrating lift starts to fall. The profile is fully stalled, and the air flow is separated all over the rear side of the blade at about 20 degrees. These figures can greatly vary from profile to profile and also between different thicknesses of the same profile.

When the stall phenomena is used to restrict power output, as in all Bonus wind turbines, it is important that blades are trimmed correctly. With the steep lift curve, the angle of attack cannot be altered very much, before maximum output also changes, therefore it is essential that the angle of the blade is set at the correct value.

One cannot alter the different angles on the blade itself, once the form, shape and blade molding has been decided upon and fabricated. So we normally talk about calibrating the tip angle. Not because the blade tip has any special magical properties, but we can place a template at the tip, which allows us to make measurements using a theodolite. Adjusting of the tip angle can therefore be understood as an example of how the angle of the total blade is adjusted.

Of importance for power output limitation is also the fact that in practice lift and drag normally behave exactly as would be expected from the theoretical calculations. However this is not always the case. Separation can often occur before expected, for instance due to dirt on the leading edges, or it can be delayed if the air flow over the profile for some reason or other, is smoother than usual. When separation occurs before expected, the maximum obtainable lift is not as high as otherwise expected and therefore maximum output is lower. On the other hand, delayed separation can cause continuous excessive power production output.

Accordingly profile types chosen for our blades have stable stall characteristics with little tendency to unforeseen changes. From time to time, however, it is sometimes necessary to actively alter the stall process. This is normally done by alteration to the leading edge, so that a small well-defined extra turbulence across the profile is induced. This extra turbulence gives a smoother stall process.

Turbulence can be created by an area of rougher blade surface, or a triangular strip, fixed on the leading edge. This stall strip acts as a trigger for the stall so that separation occurs simultaneously all over the rear side.

On a wind turbine blade, different air flows over the different profile shapes, interact with each other out along the blade and therefore, as a rule, it is only necessary to alter the leading edge on a small section of the blade. This altered section will then produce a stall over the greater part of the blade. For example, the Bonus 450 kW Mk III turbine, is usually equipped with a 0.5 meter stall strib, which controls the stall process all over the 17 meter long blade.

SUMMARY

The main points as described in this article can be shortly stated in the following:

- The air flow around a wind turbine blade is completely dominated by the head wind from the rotational movement of the blade through the air.

- The blade aerodynamic profile produces lift because of its streamlined shape. The rear side is more curved than the front side.

- The lift effect on the blade aerodynamic profile causes the forces of the air to point in the correct direction.

- The blade width, thickness, and twist is a compromise between the need for streamlining and the need for strength.

- At constant shaft speed, in step with the grid, the angle of attack increases with increasing wind speed. The blade stalls when the angle of attack exceeds 15 degrees. In a stall condition the air can no longer flow smoothly or laminar over the rear side of the blade, lift therefore falls and drag increases.