

Wind Turbine Blade Aerodynamics

Wind turbine blades are shaped to generate the maximum power from the wind at the minimum cost. Primarily the design is driven by the aerodynamic requirements, but economics mean that the blade shape is a compromise to keep the cost of construction reasonable. In particular, the blade tends to be thicker than the aerodynamic optimum close to the root, where the stresses due to bending are greatest.

The blade design process starts with a “best guess” compromise between aerodynamic and structural efficiency. The choice of materials and manufacturing process will also have an influence on how thin (hence aerodynamically ideal) the blade can be built. For instance, prepreg carbon fibre is stiffer and stronger than infused glass fibre. The chosen aerodynamic shape gives rise to loads, which are fed into the structural design. Problems identified at this stage can then be used to modify the shape if necessary and recalculate the aerodynamic performance.

The Wind

It might seem obvious, but an understanding of the wind is fundamental to wind turbine design. The power available from the wind varies as the cube of the wind speed, so twice the wind speed means eight times the power. This is why sites have to be selected carefully: below about 5m/s (10mph) wind speed there is not sufficient power in the wind to be useful. Conversely, strong gusts provide extremely high levels of power, but it is not economically viable to build machines to be able to make the most of the power peaks as their capacity would be wasted most of the time. So the ideal is a site with steady winds and a machine that is able to make the most of the lighter winds whilst surviving the strongest gusts.

As well as varying day-to-day, the wind varies every second due to turbulence caused by land features, thermals and weather. It also blows more strongly higher above the ground than closer to it, due to surface friction. All these effects lead to varying loads on the blades of a turbine as they rotate, and mean that the aerodynamic and structural design needs to cope with conditions that are rarely optimal.

By extracting power, the turbine itself has an effect on the wind: downwind of the turbine the air moves more slowly than upwind. The wind starts to slow down even before it reaches the blades, reducing the wind speed through the “disc” (the imaginary circle formed by the blade tips, also called the swept area) and hence reducing the available power. Some of the wind that was heading for the disc diverts around the slower-moving air and misses the blades entirely. So there is an optimum amount of power to extract from a given disc diameter: try to take too much and the wind will slow down too much, reducing the available power. In fact the ideal is to reduce the wind speed by about two thirds downwind of the turbine, though even then the wind just before the turbine will have lost about a third of its speed. This allows a theoretical maximum of 59% of the wind’s power to be captured (this is called Betz’s limit). In practice only 40-50% is achieved by current designs.

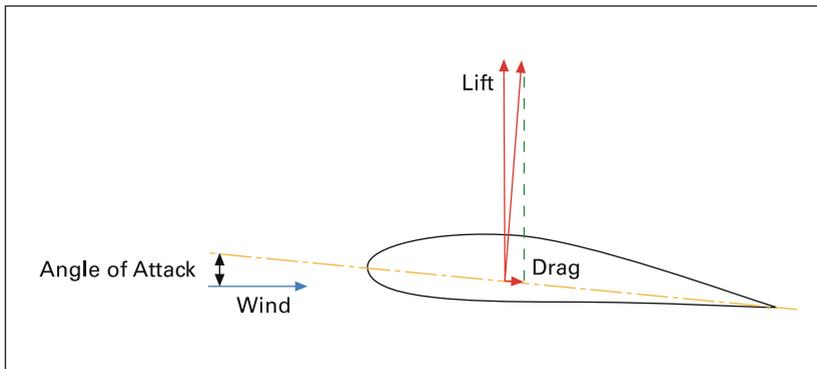
Number of blades

The limitation on the available power in the wind means that the more blades there are, the less power each can extract. A consequence of this is that each blade must also be narrower to maintain aerodynamic efficiency. The total blade area as a fraction of the total swept disc area is called the solidity, and aerodynamically there is an optimum solidity for a given tip speed; the higher the number of blades, the narrower each one must be. In practice the optimum solidity is low (only a few percent) which means that even with only three blades, each one must be very narrow. To slip through the air easily the blades must be thin relative to their width, so the limited solidity also limits the thickness of the blades. Furthermore, it becomes difficult to build the blades strong enough if they are too thin, or the cost per blade increases significantly as more expensive materials are required.

For this reason, most large machines do not have more than three blades. The other factor influencing the number of blades is aesthetics: it is generally accepted that three-bladed turbines are less visually disturbing than one- or two-bladed designs.

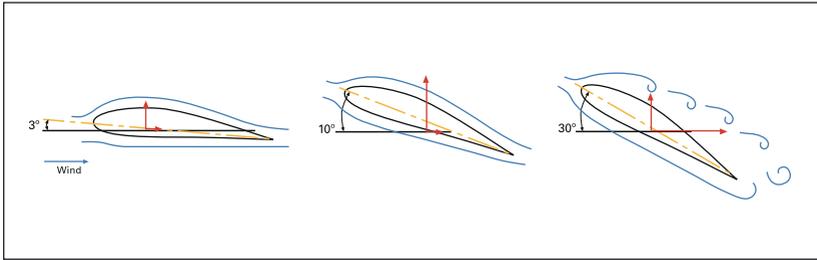
How blades capture wind power

Just like an aeroplane wing, wind turbine blades work by generating lift due to their shape. The more curved side generates low air pressures while high pressure air pushes on the other side of the aerofoil. The net result is a lift force perpendicular to the direction of flow of the air.



Lift & drag vectors

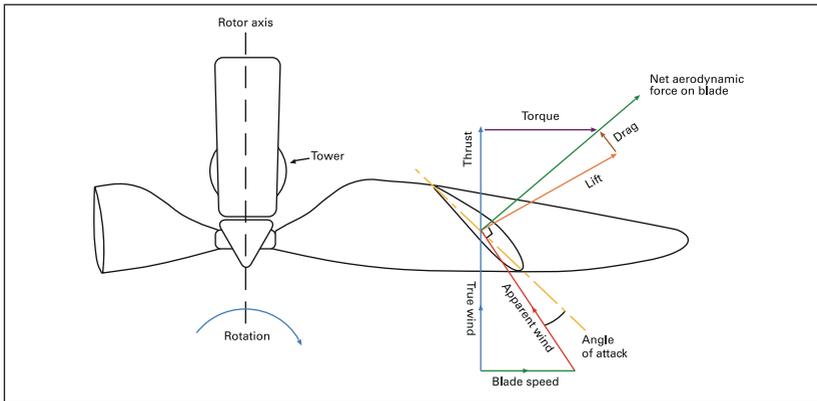
The lift force increases as the blade is turned to present itself at a greater angle to the wind. This is called the angle of attack. At very large angles of attack the blade “stalls” and the lift decreases again. So there is an optimum angle of attack to generate the maximum lift.



Blade at low, medium & high angles of attack

There is, unfortunately, also a retarding force on the blade: the drag. This is the force parallel to the wind flow, and also increases with angle of attack. If the aerofoil shape is good, the lift force is much bigger than the drag, but at very high angles of attack, especially when the blade stalls, the drag increases dramatically. So at an angle slightly less than the maximum lift angle, the blade reaches its maximum lift/drag ratio. The best operating point will be between these two angles.

Since the drag is in the downwind direction, it may seem that it wouldn't matter for a wind turbine as the drag would be parallel to the turbine axis, so wouldn't slow the rotor down. It would just create "thrust", the force that acts parallel to the turbine axis hence has no tendency to speed up or slow down the rotor. When the rotor is stationary (e.g. just before start-up), this is indeed the case. However the blade's own movement through the air means that, as far as the blade is concerned, the wind is blowing from a different angle. This is called apparent wind. The apparent wind is stronger than the true wind but its angle is less favourable: it rotates the angles of the lift and drag to reduce the effect of lift force pulling the blade round and increase the effect of drag slowing it down. It also means that the lift force contributes to the thrust on the rotor.

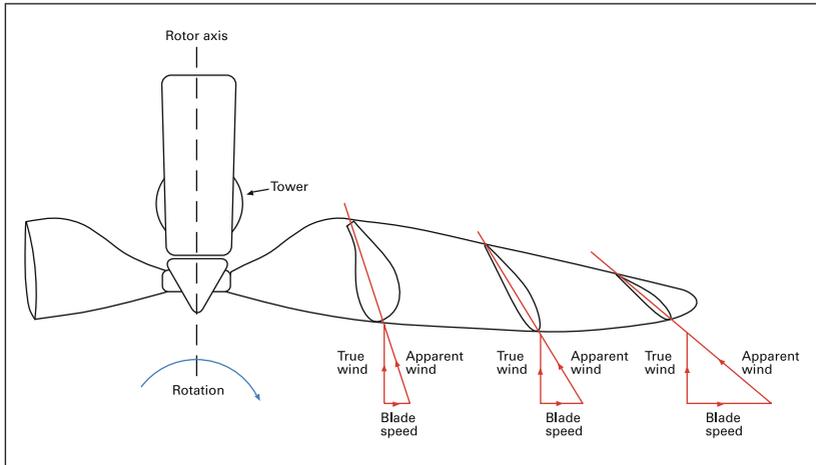


Apparent wind angles

The result of this is that, to maintain a good angle of attack, the blade must be turned further from the true wind angle.

Twist

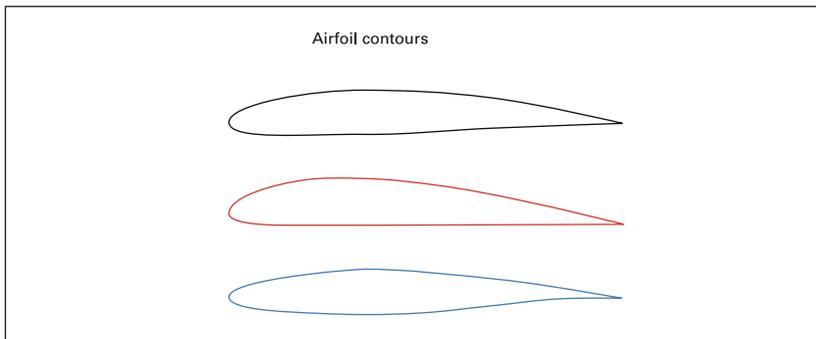
The closer to the tip of the blade you get, the faster the blade is moving through the air and so the greater the apparent wind angle is. Thus the blade needs to be turned further at the tips than at the root, in other words it must be built with a twist along its length. Typically the twist is around $10\text{-}20^\circ$ from root to tip. The requirement to twist the blade has implications on the ease of manufacture.



Blade twist

Blade section shape

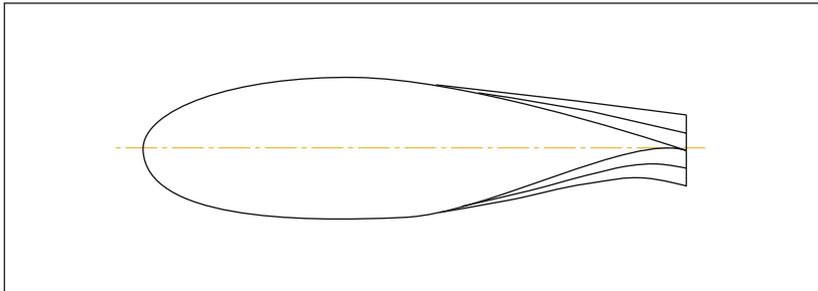
Apart from the twist, wind turbine blades have similar requirements to aeroplane wings, so their cross-sections are usually based on a similar family of shapes. In general the best lift/drag characteristics are obtained by an aerofoil that is fairly thin: its thickness might be only $10\text{-}15\%$ of its "chord" length (the length across the blade, in the direction of the wind flow).



Typical aerofoil shapes offering good lift/drag ratio

If there were no structural requirements, this is how a wind turbine blade would be proportioned, but of course the blade needs to support the lift, drag and gravitational forces acting on it. These structural requirements generally mean the aerofoil needs to be thicker than the aerodynamic optimum, especially at locations towards the root (where the blade attaches to the hub) where the bending forces are greatest. Fortunately that is also where the apparent wind is moving more slowly and the blade has the least leverage over the hub, so some aerodynamic inefficiency at that point is less serious than it would be closer to the tip. Having said this, the section can't get too thick for its chord length or the air flow will "separate" from the back of the blade – similar to what happens when it stalls – and the drag will increase dramatically.

To increase thickness near the root without creating a very short, fat, aerofoil section, some designs use a "flatback" section. This is either a standard section thickened up to a square trailing (back) edge, or a longer aerofoil shape that has been truncated. This reduces the drag compared to a rounder section, but can generate more noise so its suitability depends on the wind farm site.



Typical "flatback" aerofoil shape

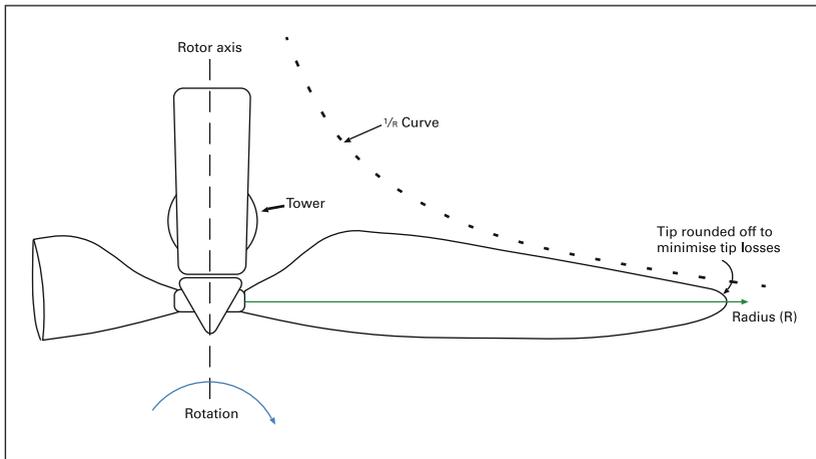
There is a trade-off to be made between aerodynamic efficiency and structural efficiency: even if a thin blade can be made strong and stiff enough by using lots of reinforcement inside, it might still be better to make the blade a bit thicker (hence less aerodynamically efficient) if it saves so much cost of material that the overall cost of electricity is reduced. The wind is free after all; it's only the machine that we have to pay for. So there is inevitably some iteration in the design process to find the optimum thickness for the blade.

Blade planform shape

The planform shape is chosen to give the blade an approximately constant slowing effect on the wind over the whole rotor disc (i.e. the tip slows the wind to the same degree as the centre or root of the blade). This ensures that none of the air leaves the turbine too slowly (causing turbulence), yet none is allowed to pass through too fast (which would represent wasted energy). Remembering Betz's limit discussed above, this results in the maximum power extraction.

Because the tip of the blade is moving faster than the root, it passes through more volume of air, hence must generate a greater lift force to slow that air down enough. Fortunately, lift increases with the square of speed so its greater speed more than allows for that. In reality the blade can be narrower close to the tip than near the root and still generate enough lift. The optimum tapering of the blade planform as it goes outboard can be calculated; roughly speaking the chord should be inverse to the radius. So if the chord was 2m at 10m radius, it should be 10m at 1m radius. This relationship breaks down close to the root and tip, where the optimum shape changes to account for tip losses.

In reality a fairly linear taper is sufficiently close to the optimum for most designs, structurally superior and easier to build than the optimum shape.

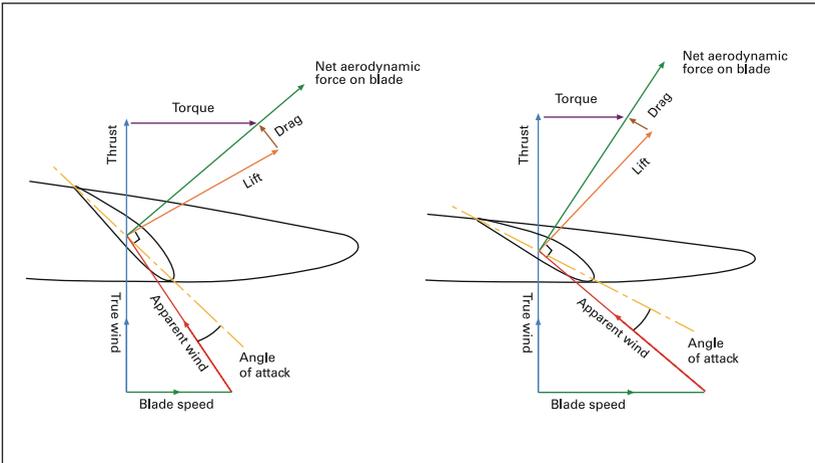


Optimum blade planform

Rotational speed

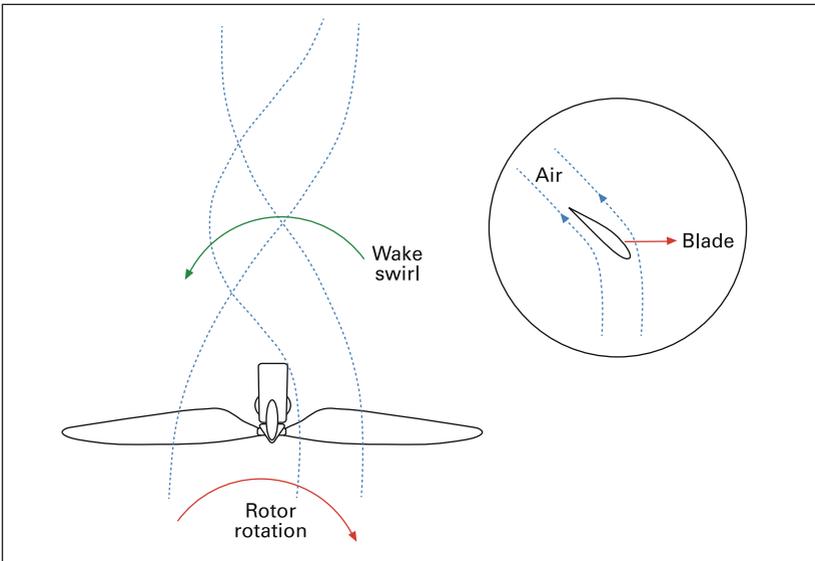
The speed at which the turbine rotates is a fundamental choice in the design, and is defined in terms of the speed of the blade tips relative to the "free" wind speed (i.e. before the wind is slowed down by the turbine). This is called the tip speed ratio.

High tip speed ratio means the aerodynamic force on the blades (due to lift and drag) is almost parallel to the rotor axis, so relies on a good lift/drag ratio. The lift/drag ratio can be affected severely by dirt or roughness on the blades.



Effect of tip speed ratio on sensitivity to drag

Low tip speed ratio would seem like a better choice but unfortunately results in lower aerodynamic efficiency, due to two effects. Because the lift force on the blades generates torque, it has an equal but opposite effect on the wind, tending to push it around tangentially in the other direction. The result is that the air downwind of the turbine has "swirl"; i.e. it spins in the opposite direction to the blades. That swirl represents lost power so reduces the available power that can be extracted from the wind. Lower rotational speed requires higher torque for the same power output, so lower tip speed results in higher wake swirl losses.



Swirl in the wake

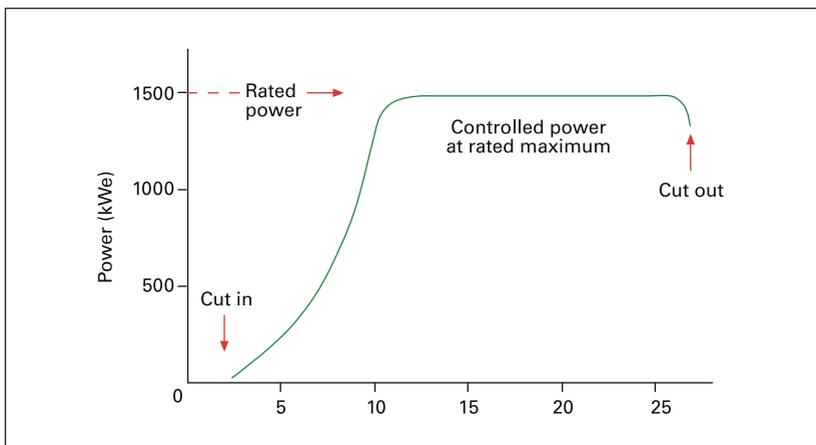
The other reduction in efficiency at low tip speed ratio comes from tip losses, where high-pressure air from the upwind side of the blade escapes around the blade tip to the low-pressure side, thereby wasting energy. Since power = force x speed, at slower rotational speed the blades need to generate more lift force to achieve the same power. To generate more lift for a given length the blade has to be wider, which means that, geometrically speaking, a greater proportion of the blade's length can be considered to be close to the tip. Thus more of the air contributes to tip losses and the efficiency decreases. Various techniques can be used to limit tip losses such as winglets (commonly seen on airliners) but few are employed in practice owing to their additional cost.

The higher lift force on a wider blade also translates to higher loads on the other components such as the hub and bearings, so low tip speed ratio will increase the cost of these items. On the other hand the wide blade is better able to carry the lift force (as discussed previously), so the blade itself may be cheaper.

All this means that turbine designers typically compromise on tip speed ratios in the region of 7-10, so at design wind speed (usually 12-15 metres per second) the blade tip can be moving at around 120 m/s (approximately 270 miles per hour). There are practical limits on the absolute tip speed too: at these speeds, bird impacts and rain erosion start to become a problem for the longevity of the blades and noise increases dramatically with tip speed.

Power and pitch control

For an economical design, the maximum performance of the generator and gearbox need to be limited to an appropriate level for the turbines operating environment. The ideal situation is for the turbine to be able to extract as much power as possible from the wind up to the rated power of the generator, then limit the power extraction at that level as the wind increases further.



Turbine Power Curve

If the blades' angle is kept constant, the turbine is unable to respond to changes in wind speed. Not only does this make it impossible to maintain an optimum angle of attack to generate the maximum power at varying wind speeds, the only way to "depower" the machine in high wind speeds is by relying on the blades to stall (known as passive stall control). This doesn't give the perfectly flat power curve above the rated wind speed shown in the graph above, so to limit the maximum power, a passive stall-controlled turbine will usually be operating somewhat below its maximum potential.

If instead the blades are attached via a bearing that allows the angle of attack to be varied (active pitch control), the blades can be angled to maintain optimum efficiency right up to the design wind speed (at which the generator is producing its rated output). Above that wind speed they can be "feathered", i.e. rotated in pitch to decrease their angle of attack and hence their lift, so controlling the power. In survival conditions, the turbine can be stopped altogether and the blades feathered to produce no turning force at all.

An alternative to decreasing the angle of attack above the design wind speed is deliberately to increase it to the point where the blade stalls (active stall control). This decreases lift and increases drag, so has the desired slowing effect on blade rotation. It is also less sensitive to gusts of wind than feathering: by decreasing the apparent wind angle, gusts increase the angle of attack so tend to make the blade stall more. Therefore controlling blade speed by stall rather than feathering can be beneficial in gusty conditions. Both methods are used by different designs.

In Summary

- **Length:** The blade length determines how much wind power can be captured, according to the "swept area" of the rotor disc. Of all the energy in the wind, only about half can realistically be extracted (Betz's limit).
- **Aerodynamic Section:** The blades have an aerodynamic profile in cross section to create lift and rotate the turbine.
- **Planform Shape:** The planform shape gets narrower towards the tip to maintain a constant slowing effect across the swept area. This ensures that none of the air leaves the turbine too slowly (causing turbulence), yet none is allowed to pass through too fast (which would represent wasted energy).
- **Aerofoil Thickness:** The thickness increases towards the root to take the structural loads, in particular the bending moments. If loads weren't important then the section thickness/chord ratio would be about 10-15% along the whole length. "Flatback" sections may be used near the root to improve aerodynamic efficiency.

- **Blade Twist:** The apparent wind angle changes along the blade due to the increase in blade speed with increasing distance outboard. Hence to maintain optimum angle of attack of the blade section to the wind, it must be twisted along its length.
- **Blade Number and Rotational Speed:** Typically the rotational speed chosen so that the tips are moving at seven to ten times the wind speed, and there are usually no more than three blades.
 - Higher speeds and higher numbers of blades mean each blade must be narrower, hence thinner, which makes it harder to make them strong enough. At very high rotational speeds the blades also start to become aerodynamically inefficient, noisy and prone to erosion and bird strikes.
 - At low rotational speeds, swirl in the wake and tip losses reduce efficiency, while thrust loads on the other components increase.
- **Pitch Control:** Because the wind power varies so greatly (with the cube of wind speed), the turbine must be able to generate power in light winds and withstand the loads in much stronger winds. Therefore, above the optimum wind speed, the blades are typically pitched either into the wind (feathering) or away from the wind (active stall) to reduce the generated power and regulate the loads.