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AN OVERVIEW OF AERODYNAMIC BEHAVIOUR OF WIND TURBINE BLADE

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ABSTRACT

Wind turbine is a device that extracts kinetic from wind and converts it into mechanical energy. These can only be understood with a deep comprehension of the aerodynamics. This paper focuses primarily how the blade captures wind power. The majority of the paper details the analytical approach for the analysis of aerodynamics and performance of wind turbine blades. The analysis of aerodynamic behavior of wind turbines can be started without any specific turbine design just by considering the energy extraction process. Additionally, more advanced method “blade element momentum theory” (BEM) is also introduced briefly. A number of mathematical and analytical treatments have extended the knowledge of the physics and mechanics behind the aerodynamics forces. Actually, this article outlines briefly an overview of wind turbine blade analysis based on aerodynamic forces i.e. lift force and drag force. Indeed, the design of blade according to aerodynamic requirements is crystal clear through this paper.

KEYWORDS: Aerofoil, Aerodynamics, Angle-of-attack, BEM theory, Betz’s limit, Twist, solidity.

INTRODUCTION

The underlying physical and technological principles behind deriving power from indirect solar energy such as wind power energy sources are explained. The primary application of wind turbines is to extract energy from the wind. Hence, the aerodynamics is a very important aspect of wind turbine. Overall the details of aerodynamics depend very much on the topology and the most common topology is the horizontal-axis wind turbine (HAWT). It is a lift based wind turbine with very good performance.

AERODYNAMIC FORCES

When a force is transferred by a moving solid object to another solid object, the second object will generally move in either the same direction or in a direction at a small angle (less than 90 degree) to the direction of motion of the first object, unless subjected to another force. However, the method by which forces are transferred from a fluid to a solid object is very different.

Wind turbines are operating in an unconstrained fluid, in this case air. To understand how they work, two terms from the field of aerodynamics will be introduced. These are “drag” and “lift”. (Fig1)

An object in an air stream experiences a force that is imparted from the air stream to that object . We can consider this force to be equivalent to two component forces acting in perpendicular directions, known as the **drag force** and **lift force**. The magnitude of these drag and lift forces depends on the shape of the objects, its orientation to the direction of the air stream, and the velocity of the air stream.

The drag force is the component that is in line with the direction of the air stream. A flat plate in an air stream, for example, experiences maximum drag forces when the direction of the flow is perpendicular to the flat side of the plate, when the direction of the air stream is in the line with the flat side of the plate, the drag forces are at a minimum. Traditional vertical axis windmills and undershot water wheels are driven largely by drag forces.

The lift force is the component that is at right angles to the direction of the air stream. It is termed ‘lift’ force because it is the force that enables aeroplanes to ‘lift’ off the ground and fly, though in other applications it may include a *sideward* (as in a sailboat) or *downward* force (as in the downforce aerofoil used in some racing cars). Lift forces acting on a flat plate are smallest when the direction of the air stream is at a zero angle to the flat surface of the plate. At small angles relative to the direction of the air stream - that is, when so-called *angle-of attack* is small – a low

pressure region is created on the *downstream* or *leeward* side of the plate as a result of an increase in the air velocity on that plate.

In this situation, there is a direct relationship between air speed and pressure: the faster the airflow, the lower the pressure (i.e. the greater the 'suction pressure'). This phenomenon is known as the **Bernoulli effect**. The lift force thus acts as a *suction* or *pulling* force on the object, in a direction at right angles to the airflow. (Fig1&3)

CONCEPT OF AEROFOIL

Arching or cambering a flat plate will cause it to induce higher lift forces for a given angle-of-attack, but the use of so-called *aerofoil sections* is even more effective. There are two main types of aerofoil section that are conventionally distinguished: *asymmetrical* and *symmetrical* (Fig7).

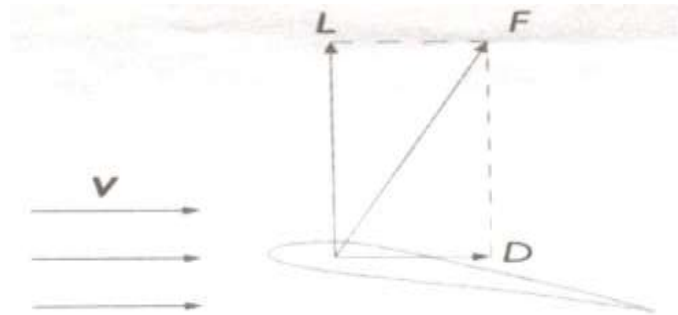


Fig 1: Drag force and Lift Force

Both have a markedly convex upper surface, a rounded end called the *leading edge* (which faces the direction from which the air stream is coming), and a pointed or sharp end called the *trailing edge*. It is the shape of the 'under surface' or high pressure side of the sections that identifies the type. Asymmetrical aerofoils are optimized to produce most lift when the underside of the aerofoil is closest to the direction from which the air is flowing. Symmetrical aerofoils are able to induce lift equally well (although in opposite directions) when the air flow is approaching from either side of the *chord line* (the length, from the tip of its leading edge to the tip of its trailing edge of an aerofoil section). (Fig2)

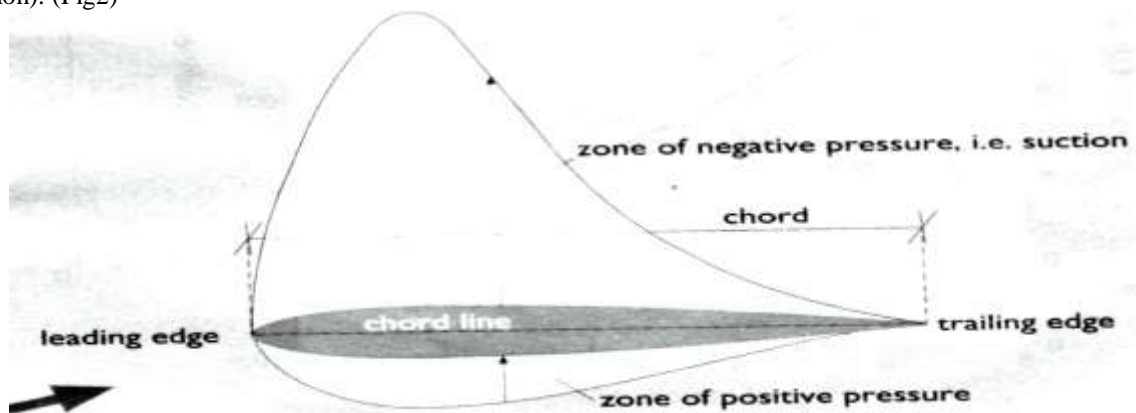


Fig 2: airfoil section in an air stream

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 winds vary 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 the 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 blade, reducing the wind speed through the 'disc' (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 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 *solidity*, and aerodynamically there is an optimum solidity for a given *tip speed*; the higher number of blades, the narrower each 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 very 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 too thin, or the cost per blade increases significantly as more expensive material are required.

For this reason, most large machines do not have more than three blades. The other factor influencing the number of blades 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 airfoil. The net result is a lift force perpendicular to the direction of flow of the air.

The lift force increases as the blade is turned to present itself at a greater angle to wind. This is called the 'angle of attack'. At every large angles-of-attack the blade 'stalls' and the lift decrease again. So there is a optimum angle-of-attack to generate the maximum lift. (Fig 3)

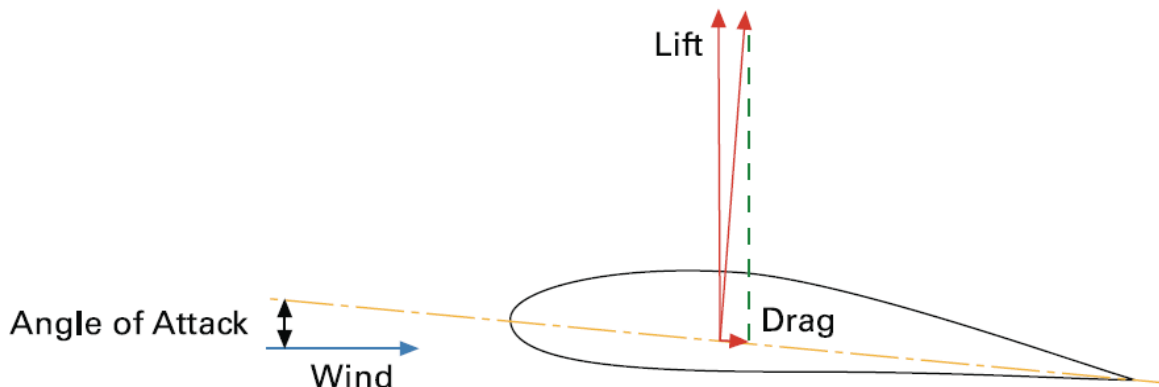


Fig 3: Lift & Drag Vector

There is, unfortunately, also a retarding force on the blade: drag force. This is the force parallel to the wind flow, and also increases with angle-of-attack. If the airfoil shape is good, the lift force is much bigger than the drag, but at a very high angle-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. (Fig 4)

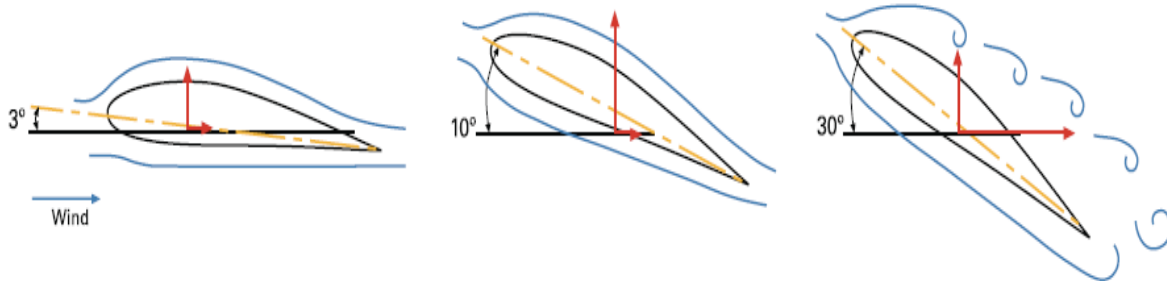


Fig 4: Blade at low, medium and high angle-of-attack

Since the drag is in the downward direction, it may seem that it would not matter for a wind turbine as the drag would be parallel to the turbine axis, so would not slow the rotor. 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 (Fig5). The apparent wind is stronger than true wind but its angle is less favourable : it rotates the angle 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.

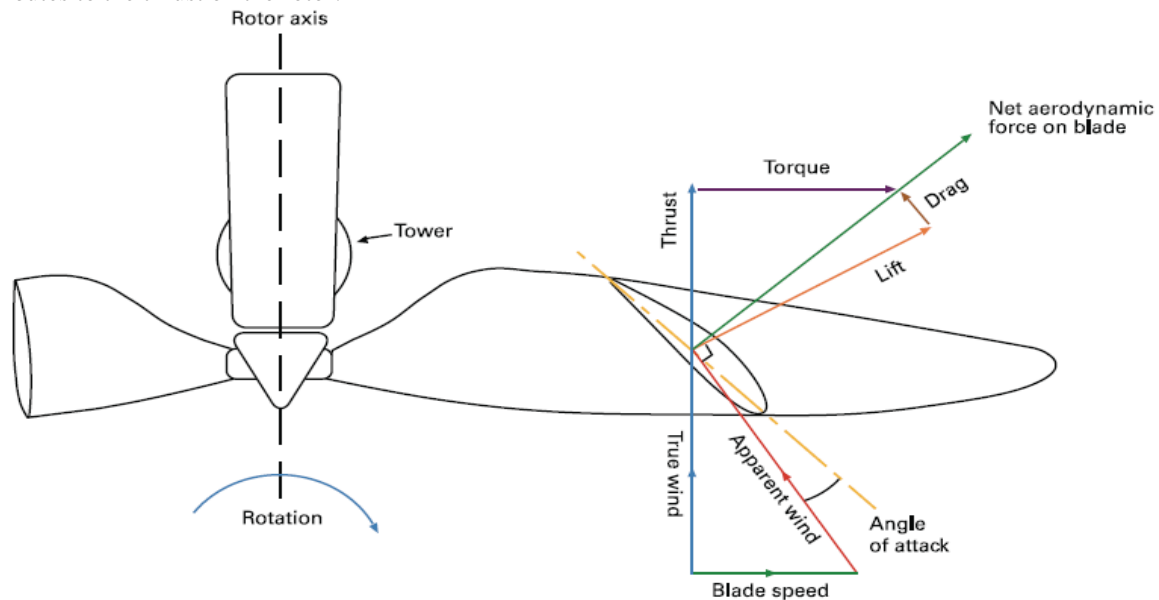


Fig 5: Apparent wind angle

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 the root, in other words it must be built with a twist along its length. Typically, the twist is around 10-20 degree from the root to tip. The requirement to twist the blade has implications on the ease of manufacture. (Fig6)

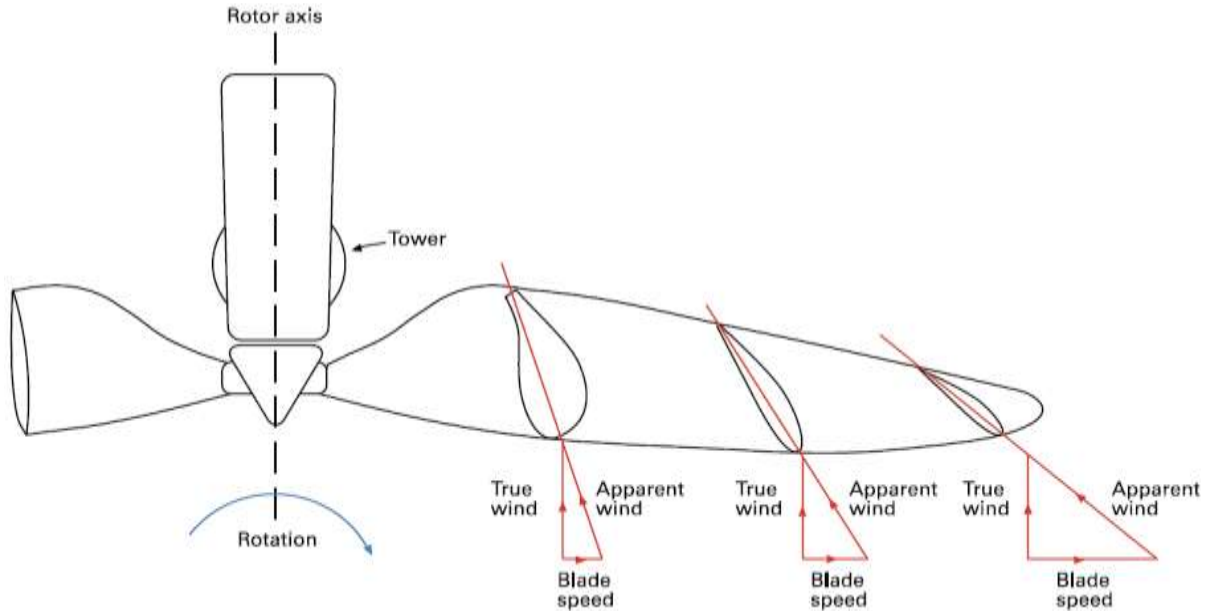


Fig 6: Blade Twist

BLADE SECTION SHAPE

Apart from 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 airfoil that is fairly thin: its thickness might be only 10-15% of its ‘chord’ length (the length across the blade, in the direction of the wind flow). (Fig2)

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 airfoil 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.

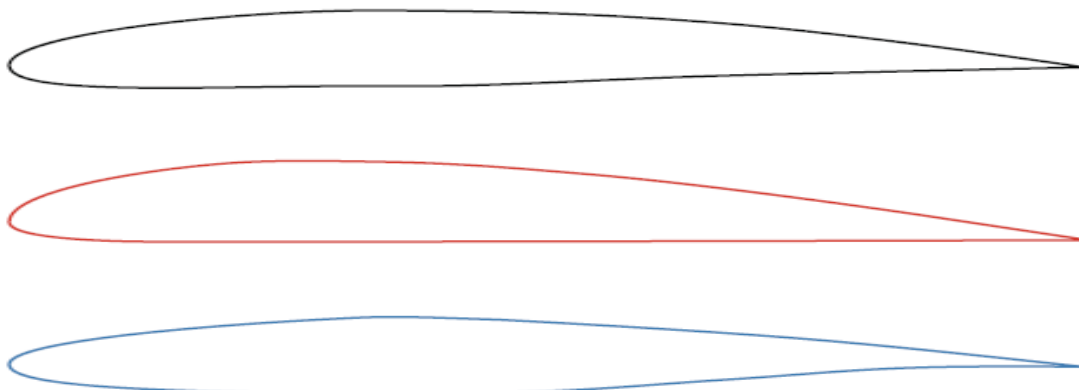


Fig 7: Typical aerofoil shape offering good lift/drag ratio

To increase thickness near the root without creating a very short, fat, airfoil 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. (Fig8)

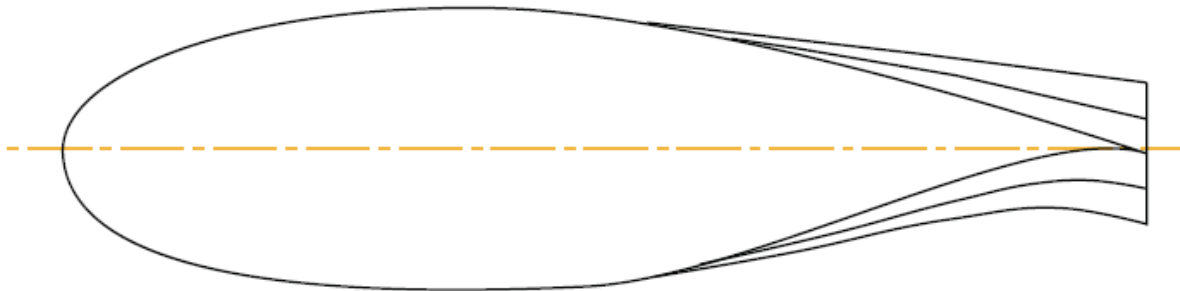


Fig 8: Typical 'flatback' aerofoil shape

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 center or root of the blade). This ensures that none of the air leaves the turbine too slowly (causing turbulence), 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.

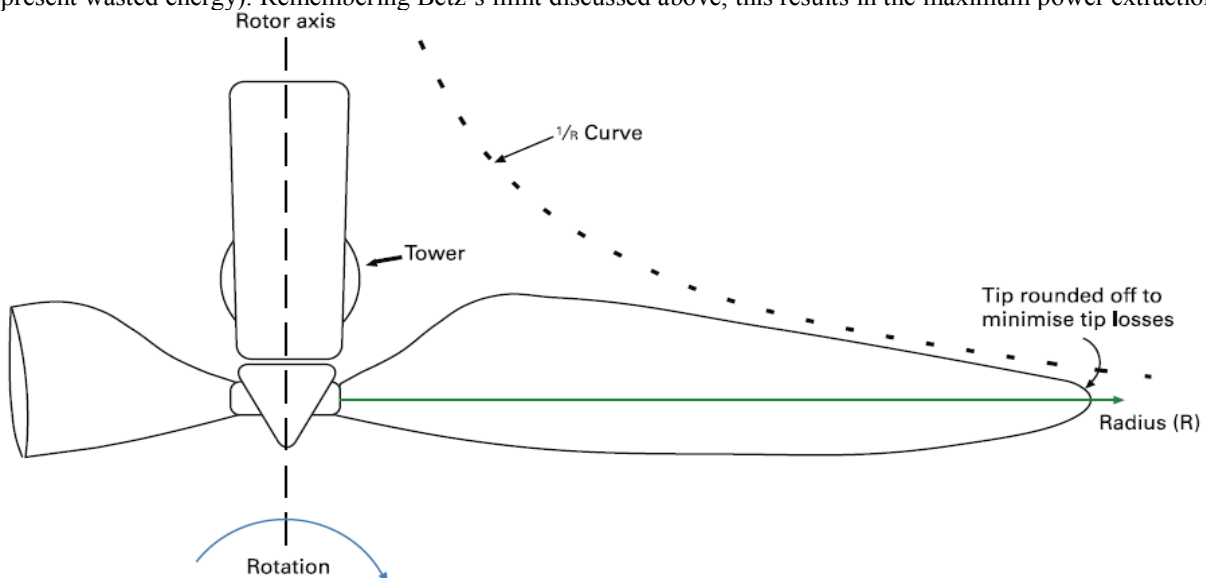


Fig 9: Optimum Blade Planform shape

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 inversely proportional 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. (Fig9) Indeed, a fairly linear taper is sufficiently close to the optimum for most designs, structurally superior and easier to build than the optimum shape.

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 called the tip speed ratio. (Fig 10)

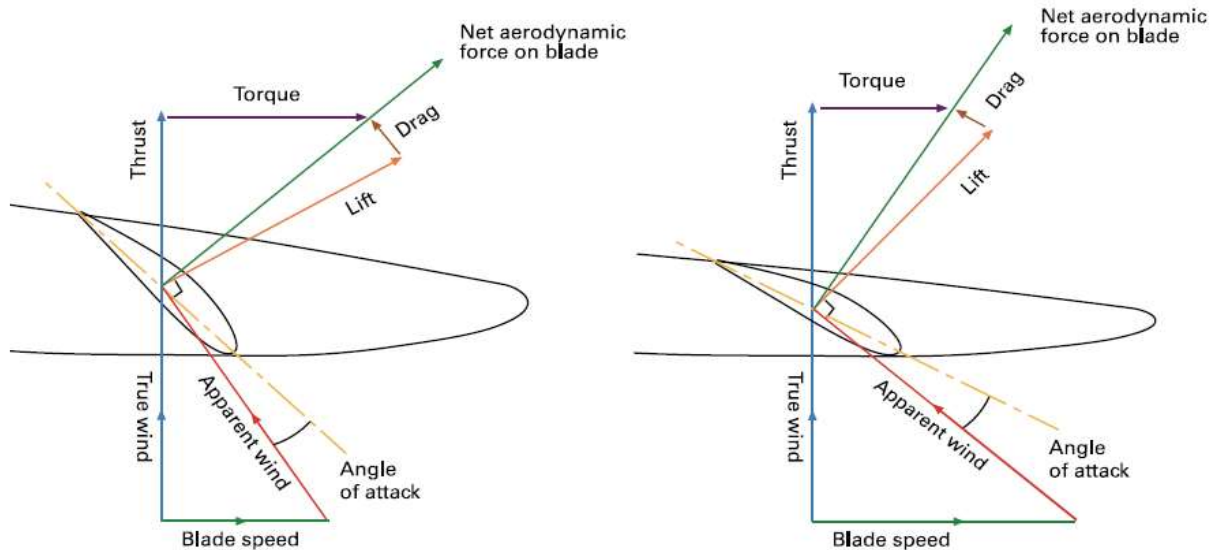


Fig 10: Effect of tip speed ratio on sensitivity to drag

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. 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. (Fig 11)

The other reduction in efficiency at low tip speed ratio comes from tip losses, where the high-pressure air from the upwind side of the blade escapes around the blade tip to the low-pressure side, thereby wasting of energy. Since $power = force \times speed$, at slower rotational speed the blades needs 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* but few are employed in practice owing to their additional cost.

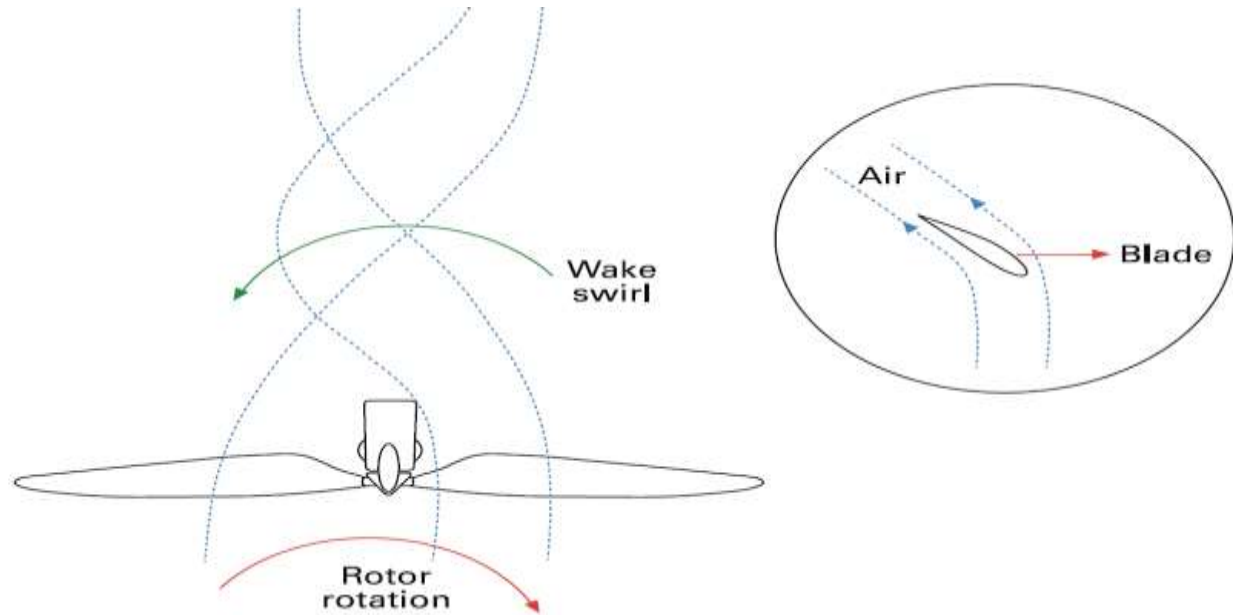


Fig 11: Swirl in the wake

The higher lift force on a wider blade also translates to higher loads on the other components such as 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, so the blade itself may be cheaper.

BEM THEORY

The simplest model for horizontal-axis-wind-turbine (HAWT) aerodynamics is blade element momentum (BEM) theory. The theory is based on the assumption that the flow at a given annulus does not affect the flow at adjacent annuli. This allows the rotor blade to be analyzed in sections, where the resulting forces are summed over all sections to get the overall forces of the rotor. The theory uses both axial and angular momentum balances to determine the flow and the resulting forces at the blade.

There is lot of variation between different versions of BEM theory. First, one can consider the effect of wake rotation or not. Second, one can go further and consider the pressure drop induced in wake rotation. Third, the tangential induction factors can be solved with a momentum equation, an energy balance or orthogonal geometric constraint; the latter a result of Biot-Savart law in vortex method. These all lead to different set of equations that need to be solved. The simplest and most widely used equations are those that consider wake rotation with the momentum equation but ignore the pressure drop from wake rotation.

$$a = \frac{1}{\frac{4}{C_n \sigma} \sin^2 \phi + 1}$$

$$a' = \frac{1}{\frac{4}{C_t \sigma} \sin \phi \cos \phi - 1}$$

Where, 'a' is the axial component of the induced flow, a' is the tangential component of the induced flow. σ is the solidity of the rotor, ϕ is the local inflow angle. C_n & C_t are the coefficient of normal forces and coefficient of tangential forces.

CONCLUSION

The kinetic energy extracted from the wind is influenced by the geometry of the rotor blades. Determining the aerodynamically optimum blade shape, or the best possible approximation to it, is one of the main tasks of the wind

turbine designers. According to this chapter sets out the basis of the aerodynamic behavior of wind turbine blade and the design methods based on this to find the best possible design compromise for the geometric shape of the blade and rotor which can only be achieved in an iterative process.

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