AERODYNAMICS OF ROTOR BLADES

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INTRODUCTION

In a modern wind machine, the preferred configuration is to place the rotor consisting of the rotor blades and the hub upwind of the nacelle and tower. The reason is that the air behind a wind turbine forms a wake much like a ship in water that is highly turbulent causing cyclic fatigue loading in a downwind configuration.

Wind machines have adopted the technology developed for the construction of airplane wings and airplane propeller blades and added some ingenious ideas of their own leading to a new and unique specialized technology. Wind machines operate in an environment totally different than airplane wings characterized with continually changing wind speed and direction.

Since the power contained in a moving air stream is proportional to the square of the rotor diameter and to the cube of the wind speed, the rotor blades must be carefully designed in order to optimally extract this power and convert it into torque that drives the electrical generator.

As the wind speed increases, it is necessary for the rotor to speed up in order to remain near the optimal tip speed ratio. At some point in wind gusts its rotation must be stopped to avoid its catastrophic failure under a runaway condition.

Figure 1. Rotor blade and hub showing its airfoil cross sectional shape.

FORCES ACTING ON ROTOR BLADES

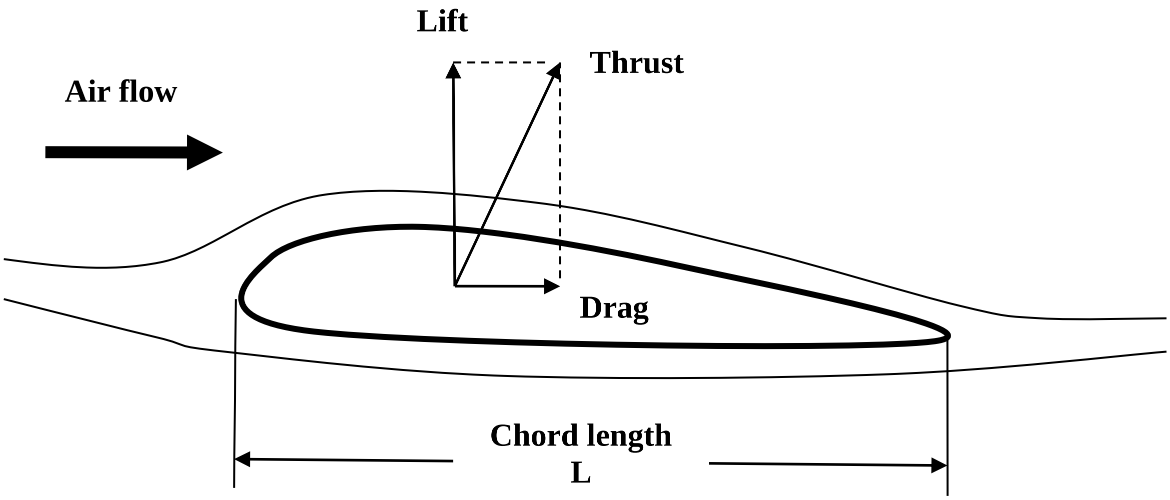

Figure 2. Forces on a stationary rotor blade in an air flow.

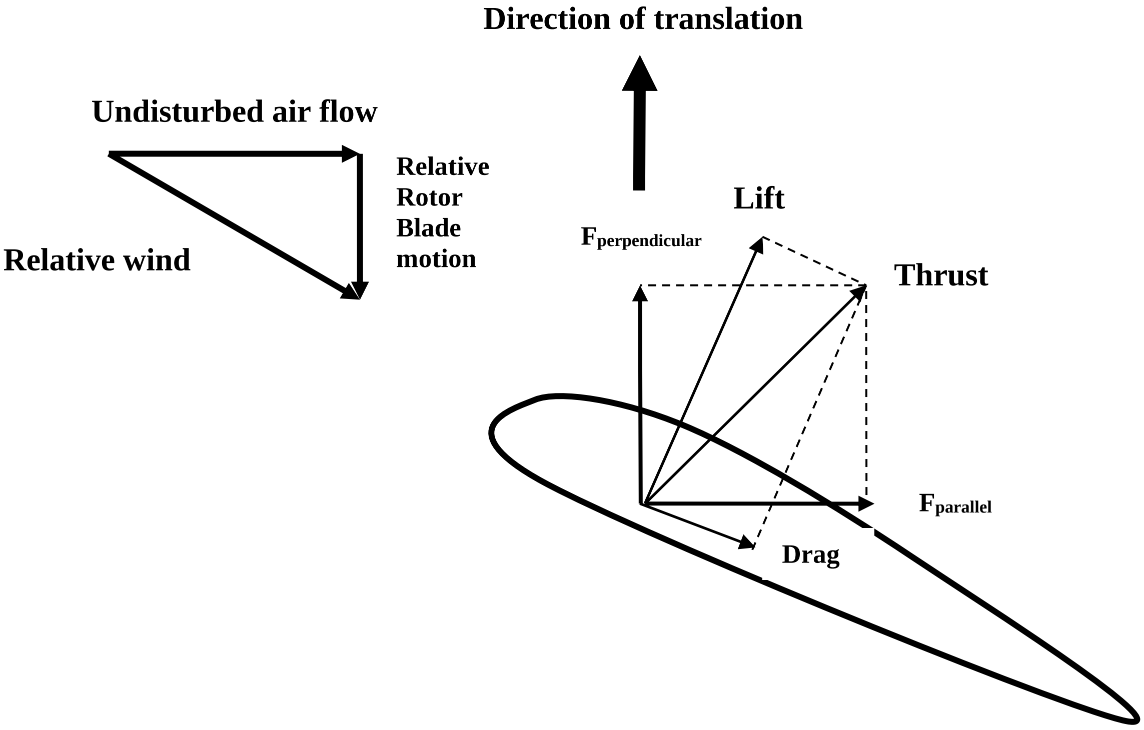

Figure 3. Parallel and perpendicular components of the lift and drag forces acting on a translating rotor blade in an air stream.

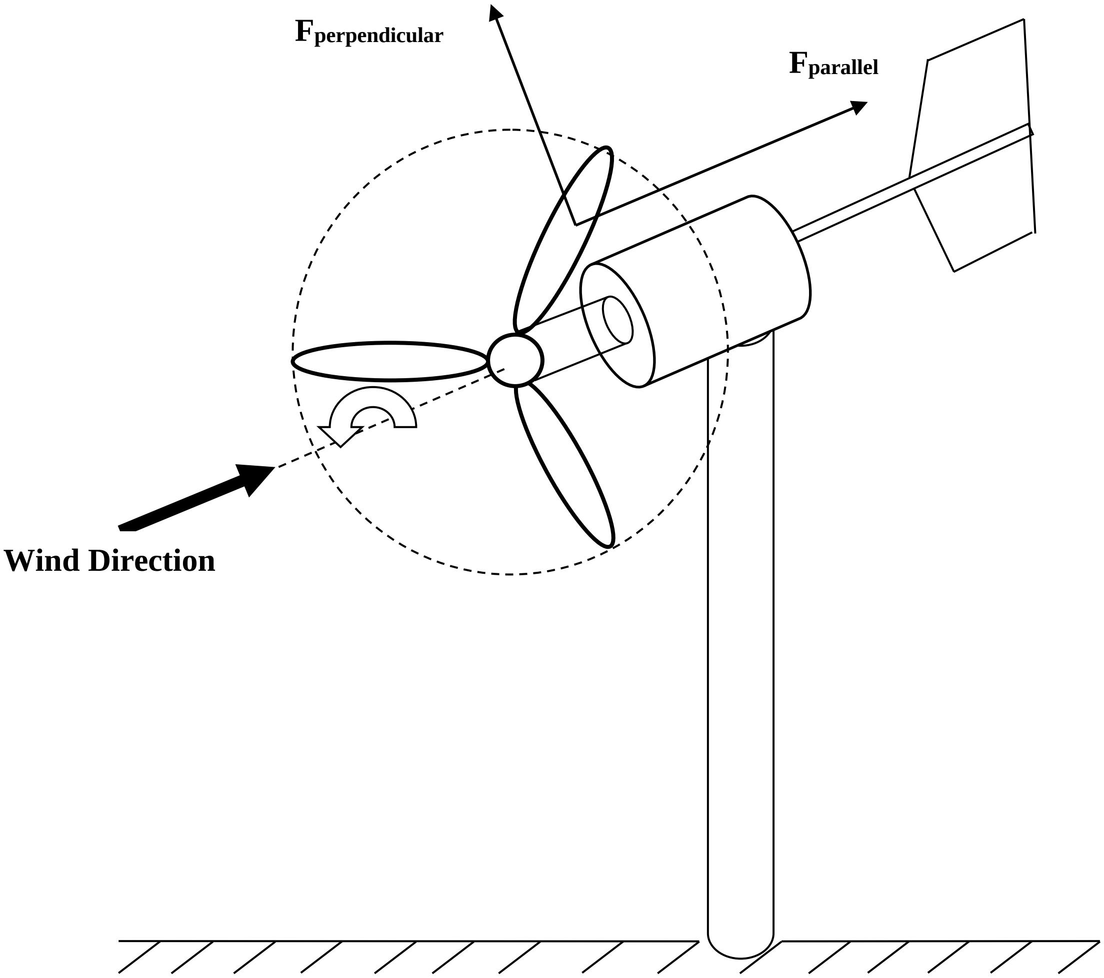

Figure 4. Rotor blades rotational action induced by the perpendicular component, and the force on the nacelle on top of the structural tower by the parallel component.

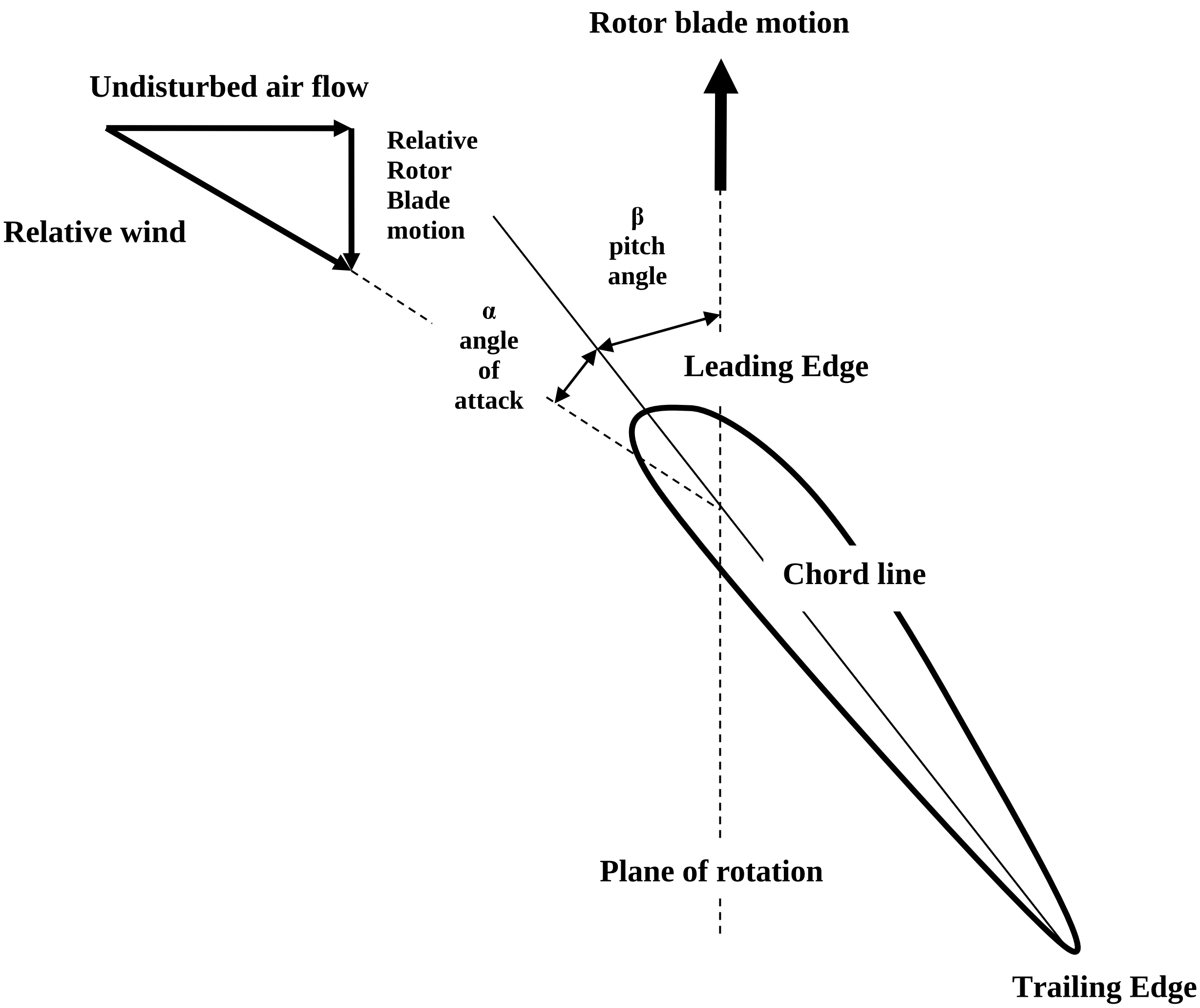

Figure 5. Pitch angle β and angle of attack α.

DIMENSIONLESS PRESSURE COEFFICIENTS

Pressure is a quantity that has a dimension of force per unit area such Newtons/m^2 or pounds/ft^2. A dimensionless pressure is useful in aerodynamics and is called the pressure coefficient C$_p$. It is defined as:

$$C_p = \frac{p - p_0}{q_0} = \frac{p - p_0}{\frac{1}{2}\rho_0 V_0^2} \qquad (1)$$

where:

p is the local pressure
q_0 is the dynamic or kinetic pressure
p_0 is the free stream static pressure

The dynamic pressure is given by Bernoulli's equation as:

$$q_0 = \frac{1}{2}\rho_0 V_0^2 \tag{2}$$

Pressures are given in the aerodynamic literature, from incompressible to hypersonic flow, in terms of the dimensionless pressure coefficient rather than in terms of the pressure per se. It is also used as a similarity parameter [2].

PRESSURE COEFFICIENT IN INCOMPRESSIBLE FLOW

In incompressible flow the pressure coefficient can be expressed in terms of the velocity alone. We take into account the flow over an aerodynamic body immersed in a free air stream with pressure p_0 and velocity V_0, and pick an arbitrary point in the flow where the pressure is p and the velocity is V. If we consider Bernoulli's Equation:

$$p_0 + \frac{1}{2}\rho_0 V_0^2 = p + \frac{1}{2}\rho V^2 = \text{constant} \tag{3}$$

If the density remains constant, we can write:

$$p - p_0 = \frac{1}{2}\rho_0 (V_0^2 - V^2) \tag{4}$$

Substituting for the definition of the pressure coefficient, we get;

$$\begin{aligned} C_p &= \frac{p - p_0}{\frac{1}{2}\rho_0 V_0^2} \\ &= \frac{\frac{1}{2}\rho_0 (V_0^2 - V^2)}{\frac{1}{2}\rho_0 V_0^2} \\ &= 1 - \left(\frac{V}{V_0}\right)^2 \end{aligned} \tag{5}$$

DRAG, LIFT AND STALL

The geometry of the rotor blade in a wind turbine determines the amount of power that can be extracted from the wind at a given speed. The shape of the cross sectional area of the rotor blade experiences several forces from the effect of the wind.

LIFT FORCE

The lift force L arises in a direction that is perpendicular to the air stream caused by the Bernoulli Effect that lowers the pressure on top of the airfoil compared with the pressure at its bottom. The curvature on the top leads to a higher stream velocity than at the bottom and hence a lower pressure.

The lift on an airfoil has been known to the ancient mariner who would let their sail form the shape of an airfoil and use the generated lift to propel their ships in the desired direction. Roofers have also long observed that the roofing material will be lifted by strong winds on the lee side of the roof if not attached properly to the roof substrate.

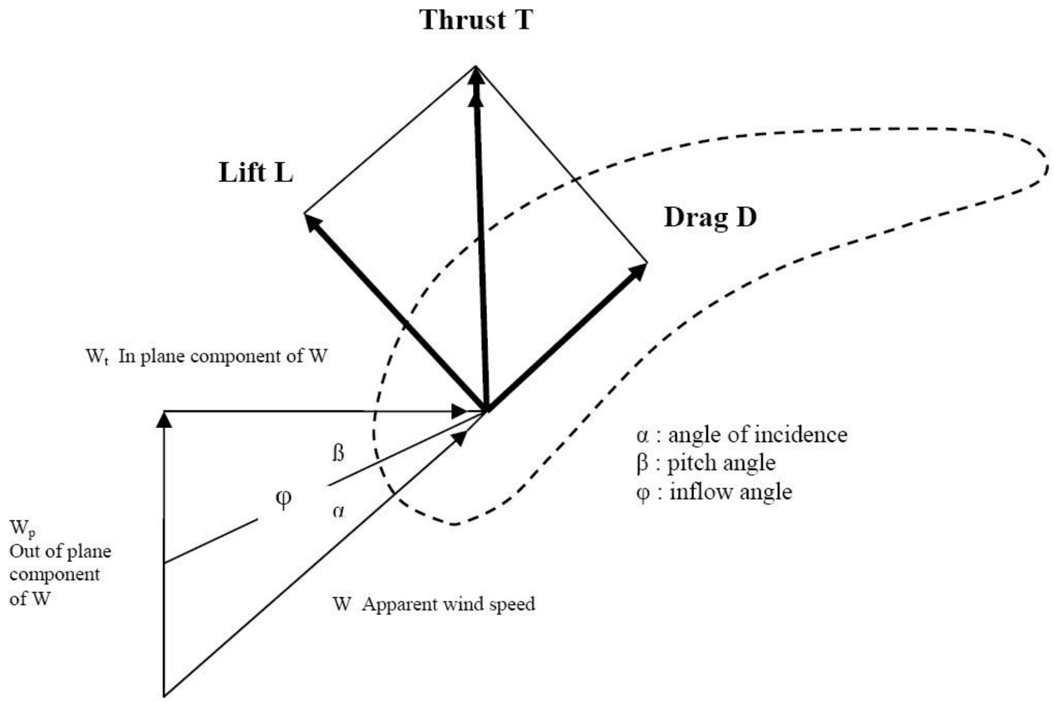

Figure 6. Geometry of forces acting on airfoil.

The lift force L is described by the lift coefficient C_L:

$$C_L = \frac{(L/A_L)}{\frac{1}{2}\rho V^2} \tag{6}$$

where:

ρ is the air density [kg/m^3]

V is the wind speed [m/sec]

A_L is the cross sectional area of the airfoil [m^2]

L is the lift force [Newtons]

DRAG FORCE

The drag force D is described by the drag coefficient C_D:

$$C_D = \frac{(D / A_D)}{\frac{1}{2}\rho V^2} \qquad (70$$

where:

A_D is the effective area of the airfoil in the drag direction [m^2]

D is the drag force [Newtons]

The lift L and drag D forces vary with the angle that the rotor blade makes with the direction of the air stream designated as the angle of attack φ.

THRUST FORCE

The resultant of the lift and drag forces constitutes the thrust force T that effectively rotates the rotor blade.

The resultant ratio of lift to drag L/D is a function of the angle of attack φ for a given airfoil section. The maximum value of the L/D ratio profile corresponds to the optimal angle of attack for attaining the maximum efficiency of the turbine rotor blade.

STALL

Aircraft pilots have observed that if they increase the angle of attack of their wing by tilting the body of the plane back, the lift increases and the plane climbs up. However if they try to do it to an excess, as the wing is tilted backwards, all of a sudden the air flow on the upper surface stops sticking to the surface of the wing and a flow separation occurs. The air rotates around the wing in a turbulent irregular vortex. Suddenly the lift from the low pressure on the upper surface of the wing disappears, and the plane stalls and starts falling off the sky instead of climbing up.

An aircraft wing loses its lift and stalls if the shape of the wing is tilted off too steeply as the air moves along its general direction of motion. The wing itself does not change its shape, but the angle of attack of the wing relative to the general direction of the airflow would have increased.

Stall can be initiated if the surface of the aircraft wing or the wind turbine rotor blade is not smooth. A dent in the wing or rotor blade, icing, or a loose piece of self adhesive tape can be enough to start the turbulence on the backside, even if the angle of attack is fairly small.

Aircraft designers try to avoid stall at all costs, since an airplane without the lift from its wings will fall from the sky. Numerous accidents have occurred to aircraft from icing on the wings changing their shape and causing them to stall. Airplanes avoid flying under icing weather conditions, and their wings get deiced by power spraying them with antifreeze solutions at airports before takeoff to avoid accidents resulting from icing stalling conditions.

Wind turbine designers take advantage of the stall condition in the control of wind turbines. They deliberately generate stall to stop the wind rotor from rotation at high speed under gusty wind conditions that could lead to its failure.

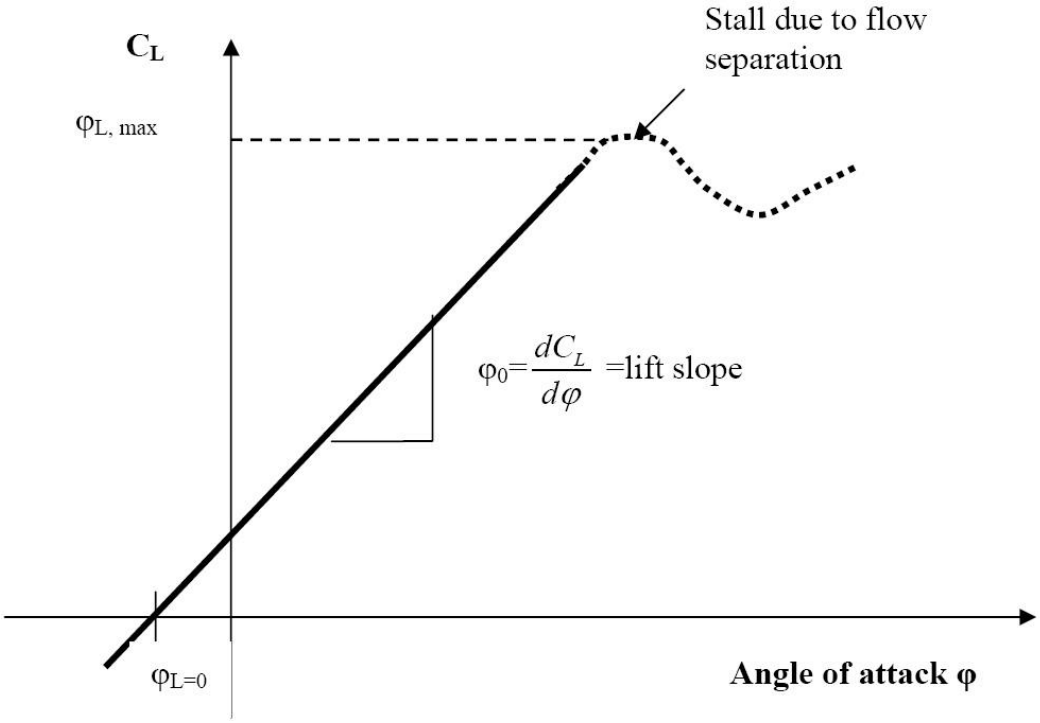

Figure 7. Lift coefficient variation as a function of the angle of attack of an airfoil. Flow due flow separation appears at $\varphi_{L,max}$.

At low to moderate angles of attack the lift coefficient varies linearly with the angle of attack. The slope of this straight line is φ_0 and is designated as the lift slope. The flow moves smoothly over the airfoil and is attached over most of the surface.

As the angle of attack becomes large, the flow separates from the top surface of the airfoil creating a large wake of relatively dead air behind the airfoil. Inside this separated region, the flow recirculates and part of it actually moves in a direction opposite to the mainstream generating a reverse flow. The separated flow is caused by the viscous effects in the flow. The curve becomes non linear, reaches a maximum value and then suddenly decreases. Its consequence is a precipitous decrease in lift and a large increase of the drag. Under this condition the airfoil is said to stall.

The maximum value of the lift coefficient obtained just before stall is denoted as $C_{L,\ max}$ and is one of the most important aspects of airfoil performance. The higher it is, the lower is the stalling speed. A great deal of research has been devoted to to increasing its value.

At the other extreme of the curve the lift at $\varphi = 0$ is finite. The lift goes down to zero only when the airfoil is pitched at some negative angle of attack. The value of the angle of attack when the lift is zero is called the zero lift angle of attack and is designated as $\varphi_{L=0}$.

For a symmetric airfoil, $\varphi_{L=0} = 0$. For all airfoils with a positive camber above the the chord line, $\varphi_{L=0}$ is negative value in the range of -2^o to -3^o.

ROTOR BLADES ICING

A small amount of snow or ice on the surface of an airfoil has a significant effect on the smooth flow of air over the surface contour. Changes in the shape and roughness of the surface cause the airflow to separate from the rotor or wing at lower angles of attack than normal. This result in a loss of lift developed at a given angle of attack and a given air speed. Both the maximum lift and the angle of attack at which it is developed will be reduced.

Since the total lift developed is a function of both air speed and angle of attack, an aircraft with snow or ice on its wings will have a higher than normal angle of attack at a given airspeed, or conversely be required to maintain a higher air speed for a given angle of attack. Stall buffet and a full stall will also occur at higher than normal air speeds.

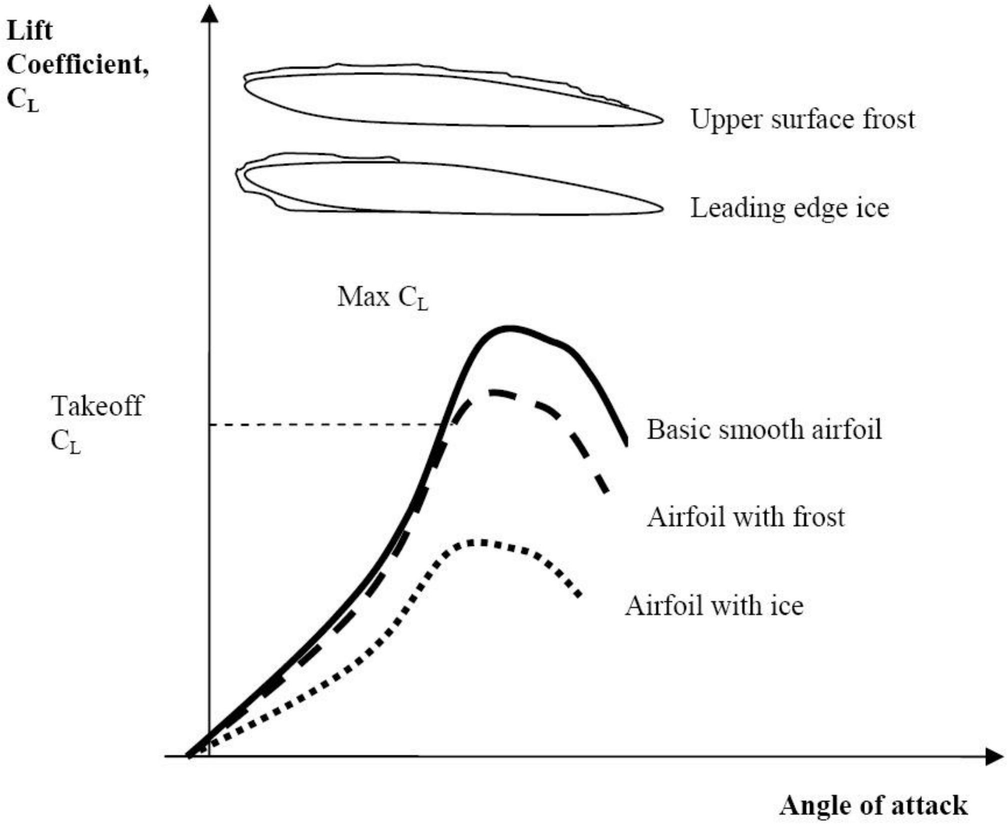

Figure 8. Effect of icing and frost on an airfoil lift coefficient and angle of attack.

The other detrimental effect of snow or ice is the increase in the total drag. The overall effects on lift efficiency and drag are further compounded by the additional weight of the snow or ice. While the lift producing capability of the wing is diminished, the lift requirement is greater because of the added weight. Since drag is a function of lift, this too is increased.

A frost encrusted wing upper surface, which roughly retains its aerofoil section loses only about 20 percent of its lift coefficient compared with a smooth wing. An iced up leading edge, on the other hand, disturbs the smooth airflow over the wing's upper surface, plays havoc with its capacity to generate lift, degrading it by some 50 percent [1].

In the case of the Boeing 737 design, the manufacturer found that even a light coating of frost on the leading edge slats could also give the aircraft a tendency to pitch up. Bulletins detailing action pilots could take to deal with the problem had been issued to Boeing 737 operators in 1974, 1979, and 1981 [1]. Ground crewmen use cherry pickers to apply deicing solutions under pressure as a mixture of ethylene glycol, propylene glycol and hot water, to remove slabs of ice that can reach 2 cm in thickness before takeoff. Heat melts the ice and snow and pressure removes it.

The Federal Aviation Administration (FAA) regulations specify that: "No person may take off an aircraft when frost, snow or ice is adhering to the wings, control surfaces, or propellers."

ROTOR BLADES MATERIALS

The majority of modern rotor blades on large wind turbines are constructed of Glass fiber Reinforced Plastics, (GRP), which is glass fiber reinforced polyester or epoxy.

Carbon or aramid fibers such as Kevlar have a high tensile strength and can be used as reinforcing materials and should lead to higher fatigue resistance. They are not used for large turbines because of their cost.

Wood, wood epoxy, or wood fiber epoxy composites are trying to penetrated the market for rotor blades.

Steel raises a weight issue and aluminum alloys generate a fatigue strength problem which makes them useful only for small wind turbines.

Figure 9. Wind rotor blade assembly.

ROTOR BLADES MANUFACTURING

Figure 10. Stored manufactured rotor blades.

Most wind turbine rotor blades are made of fiberglass reinforced epoxy. An integral blade manufacturing technology manufactures wind turbine blades in a single piece using a closed process.

The glass fiber reinforcement is laid out to dry using a special molding arrangement with a closed outer mold and an expanding inner mold. After completion of the lamination of the glass fiber, the epoxy resin is injected under a vacuum. Following this injection, the blade is hardened at a high temperature while still enclosed in the mold. Once the blade is hardened, it is removed from the outer mold, and the inner mold is collapsed with a vacuum and pulled from the blade. The result is a complete, seamless blade finished in one process.

Compared with the traditional processes, the integral blade manufacturing process offers several advantages. The process is efficient in manpower and space, requiring only one mold set for the manufacturing cycle. There are no issues related to tolerances between shells and spars. The resulting blade is an integrated structure with no glued joints that act as weak points potentially exposing the structure to cracking, water ingress and lightning.

The closed in process factory offers a clean and attractive work environment. The resins applied to the blade do not release VOCs and the risk of exposure to allergenic compounds is minimized.

ROTOR BLADE PROFILES

Rotor blade designers often use classical aircraft wing profiles as cross sections in the outer most part of the blade, but not over the whole length of the blade, which takes a twisted airfoil shape, and makes it more complex to design than airplane wings.

The thick airfoil profiles at the innermost part of the blade are designed specifically for wind turbines.

The choice of the airfoil profiles for rotor blades involves a number of compromises including reliable lift and stall characteristics, and the profile's ability to perform well even if there is some dirt on the surface which could be a problem in desert areas with no rain.

WIND ENERGY

A wind turbine extracts the wind energy from a vertical area subtended by the rotor span.

For a disc of air of mass m flowing at a speed V, the kinetic energy E of the disc is:

$$E = \frac{1}{2} m V^2 [Joules] \tag{9}$$

WIND POWER

If we are interested in the available power or energy produced per unit time, we replace the mass by the mass flow rate as:

$$P = \frac{1}{2} \dot{m} V^2 [\frac{Joules}{\sec}],[Watts] \tag{10}$$

The mass flow rate in terms of the density and the disc area is:

$$\dot{m} = \rho A V \tag{11}$$

This leads to the following equation for the power by substituting the expression for the mass flow rate:

$$P = \frac{1}{2} \rho A V^3 [\frac{Joules}{\sec}],[Watts] \tag{12}$$

If the rotor diameter is d, the area of the disc subtended by the rotor is:

$$A = \frac{\pi d^2}{4} \tag{13}$$

Thus the power available from the wind is:

$$P = \frac{1}{2} \rho \frac{\pi d^2}{4} V^3 = \frac{\pi}{8} \rho d^2 V^3 \tag{14}$$

For a reference speed V_0, we can write:

$$P_0 = \frac{\pi}{8} \rho d^2 V_0^3 \tag{15}$$

From Eqns. 14 and 15, keeping everything constant except for the wind speed, we can write for the power ratio:

$$\frac{P(V)}{P_0(V_0)} = \left(\frac{V}{V_0}\right)^3 \tag{16}$$

Thus doubling the wind speed leads to an increase in the wind power by a factor of $2^3 = 8$.

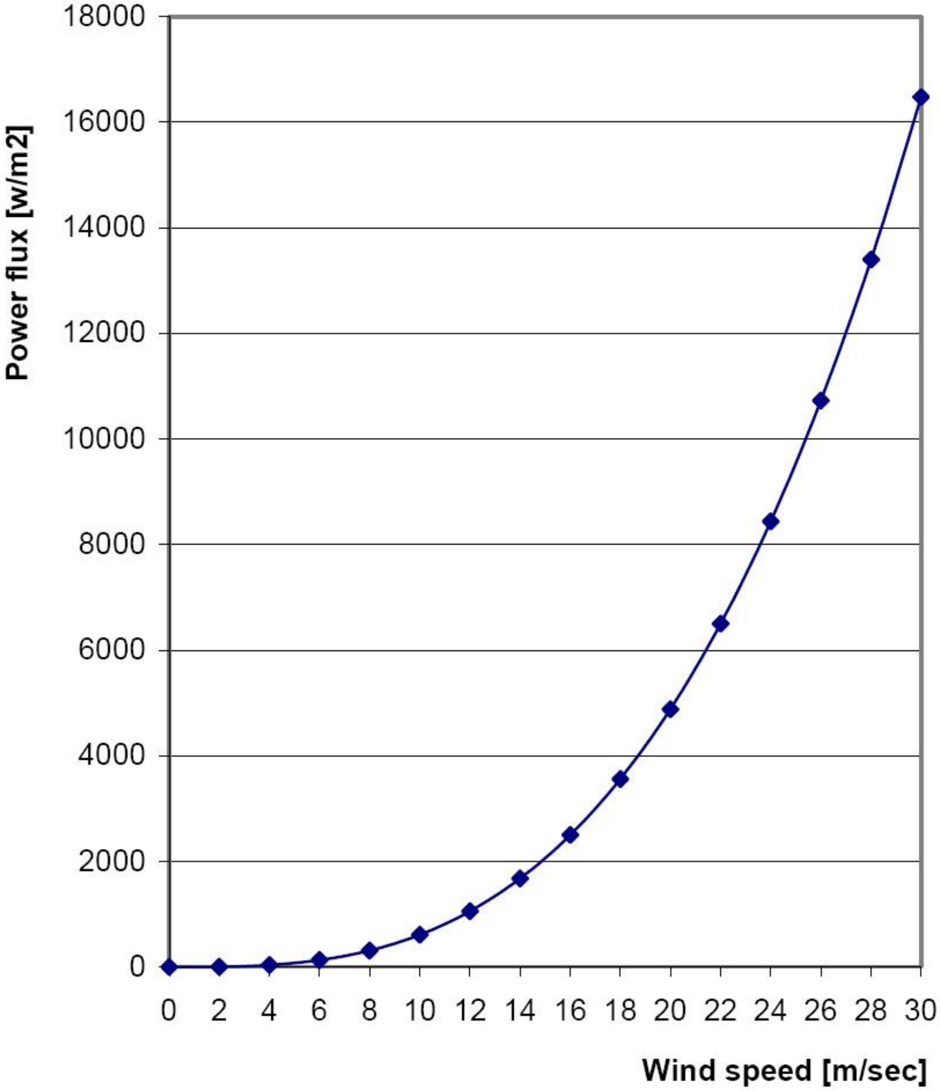

Figure 11. Increase of power flux as a function of wind speed.

WIND TURBINE ROTOR SIZES

This equation suggests that the power available is proportional to the square of the rotor diameter, as well as the cube of the wind speed.

A wind turbine with a 600 kWe generator will typically have a rotor diameter of 44 meters or 144 ft as shown in Table 1. If the rotor diameter is doubled, we get an area which is 4 times larger implying 4 times as much power output from the rotor or 2.4 MWe. In general, keeping everything else constant, the power increase is proportional to the square of the ratio of the increased diameter to the initial rotor diameter:

$$\frac{P(d)}{P_0(d_0)} = \left(\frac{d}{d_0}\right)^2 \tag{17}$$

Manufacturers optimize their machine according to the local wind conditions. A larger generator requires more power or stronger winds with a larger cut in wind speed to start rotating at all. If a wind turbine is installed in a low wind area, one would actually maximize the annual output by using a fairly small generator with a smaller cut in wind speed for a given rotor size, or a larger rotor size for a given generator. The smaller size generator would operate for a larger fraction of time than the larger generator.

For a 600 kW wind machine rotor diameters may cover the range of 39-48 meters or 128-157 feet.

Table 1. Typical generator rated powers as a function of rotor diameters.

Rotor diameter [m]	**Generator rated power [MW]**	**Theoretical power [MW] (0.6 MW turbine taken as reference)**
27	0.225	0.226
33	0.300	0.338
40	0.500	0.496
44	**0.600**	**0.600**
48	0.750	0.710
54	1.000	0.904
64	1.500	1.269
72	2.000	1.606
80	2.500	1.983
116	5.000	4.170

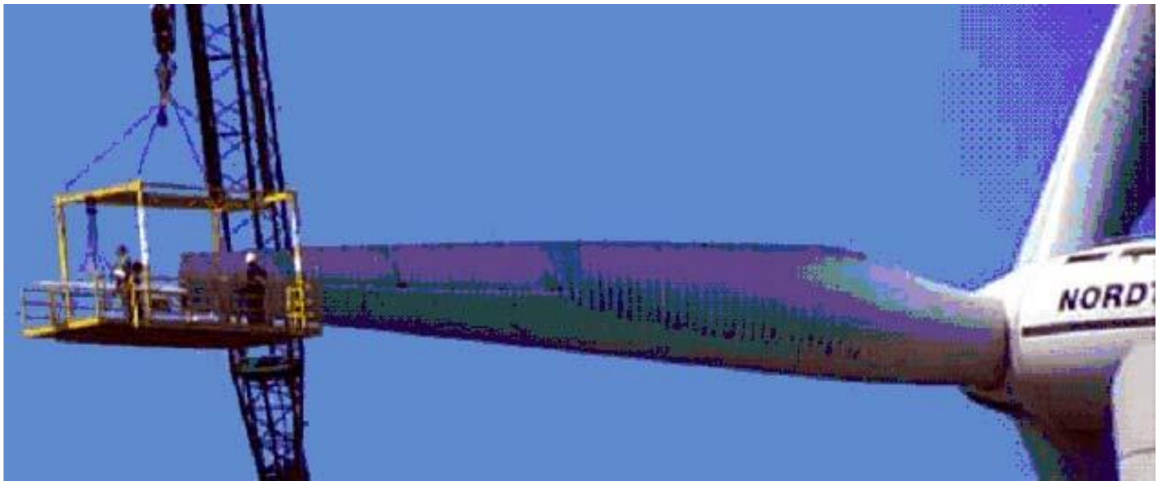

Figure 12. Maintenance operation on a 64 meters diameter wind rotor showing its relative size for a 1.5 MW wind turbine.

LARGE WIND TURBINES

Economies of scale apply in wind turbines manufacture with larger machines being able to deliver electrical energy at a lower cost/(kW.hr) than smaller machines. The cost of the supporting structures such as foundations, road building, electrical grid connection, plus a number of components in the turbine such as the electronic control system are not dependent on the size of the machine.

Larger machines are well suited for offshore wind power generation since the cost of the foundations does not rise in proportion to the size of the machine, and maintenance costs are largely independent of the size of the machine.

In locations where it is difficult to locate suitable sites for more than a single turbine, a large turbine with a tall enough structural tower would use the existing wind resource more efficiently.

SMALL WIND TURBINES

Some local limited size electrical grids may not be capable of accommodating the electrical output from a large machine such as in remote parts of the electrical grid with low populations densities and limited electricity use.

Less transients and power fluctuation in the electricity output would be encountered from a wind farm consisting of a number of smaller machines. Wind power generation fluctuations are random in nature and tend to cancel each other out.

The cost of using heavy construction equipment such as large cranes, and building road capable of accommodating the turbine components may economically favor smaller machines in some locations.

A large number of smaller machines rather than a few large ones would spread the risk in case of temporary machine failure due to storms damage or lightning strikes.

Aesthetical landscape considerations may sometimes dictate the use of smaller machines.

Large machines are characterized with a lower rotational speed than small machines implying that one large machine has a smaller signature than many small fast moving rotors in the landscape.

ROTOR EFFICIENCY, POWER COEFFICIENT AND BETZ CRITERION

The air stream moving through a turbine rotor disc cannot surrender up all of its energy to the blades. The reason is that some kinetic energy must be retained in order to move the air stream itself away from the disc area after interacting with it. The frictional effects also produce heat losses. Consequently a turbine rotor will never extract 100 percent of the energy content of the wind.

The ability of a turbine rotor to extract power from the wind depends upon its efficiency. To express the ratio of the extractable power output of the turbine P to the available power P, the non dimensional power coefficient Cp is defined as:

$$C_p = \frac{P}{E} = \frac{P}{\frac{1}{2}\rho A V^3} \qquad (18)$$

The power coefficient C_p describes the fraction of the wind's power extracted by the rotor, governed by the aerodynamic characteristics of the rotor and its number of blades.

As the air stream interacts with the rotor disc and power is extracted, the air stream speed is reduced by an amount described by the axial interference factor *a*, which is the ratio of the downstream to the upstream wind speed.

$$a = \frac{V_{down}}{V_{up}} \qquad (19)$$

In terms of the interference factor, derived elsewhere through a conservation of mass and momentum process, the power coefficient C_p is expressed as:

$$\begin{aligned} C_p &= \frac{1}{2}(1-a^2)(1+a) \\ &= \frac{1}{2}(1+a-a^2-a^3) \end{aligned} \qquad (20)$$

Differentiating with respect to *a* and equating to zero we can obtain the maximum value of C_p:

$$\begin{aligned}\frac{dC_p}{da} &= \frac{1}{2}(1-2a-3a^2) \\ &= \frac{1}{2}(1-3a)(1+a)\end{aligned} \tag{21}$$

The value a = -1 is a trivial result. We thus adopt the second solution which implies that the maximum value of C_p occurs at:

$$a = \frac{1}{3} \tag{22}$$

which means that the downstream wind speed is 1/3 of the upstream wind speed.

Hence:

$$C_{p,\max} = 4\frac{1}{3}(1-\frac{1}{3})^2 = \frac{4}{3}\frac{4}{9} = \frac{16}{27} = 0.5926 \tag{23}$$

This yields the Betz criterion for the maximum amount of power that may be extracted from the wind as 59.26 percent of the available power.

This does not tell us anything about the rotor conditions necessary to approach maximum efficiency.

AERODYNAMICS RESEARCH

BASIC AERODYNAMIC RESEARCH

The basic aim of wind turbines research and development is to be able to manufacture more cost effective machines.

Wind turbines engineers use techniques such as stall which aircraft designers try to avoid at all costs. Stall is a very complex phenomenon, because it involves airflows in three dimensions on wind turbine rotor blades. In this case the centrifugal force will induce an airflow which makes the air molecules move radially along the rotor blade from its root towards the tip of the blade.

Three dimensional (3D) computer simulations of airflows are rarely used in the aircraft industry, so wind turbine researchers have to develop new methods and computer simulation models to deal with these issues. CFD is a group of methods that simulate the air flows around rotor blades for wind turbines.

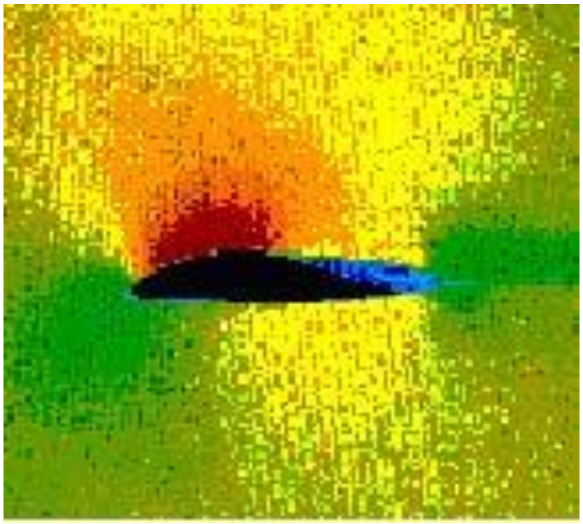

Figure 13. Wind tunnel and Computational Fluid Dynamics (CFD) simulations showing air flows and pressure distribution around a rotor blade moving towards the left.

AERODYNAMIC IMPROVEMENT DEVICES

Technologies from the aircraft industry are being adapted to improve the performance of wind turbine rotors.

An example is vortex generators, which are small fins, about 1 cm or 0.4 inch in length that are fitted to the surface of aircraft wings. The fins are alternately skewed a few degrees to the right and the left. The fins create a thin current of turbulent air on the surface of the airfoil. The spacing of the fins is chosen to ensure that the turbulent layer automatically dissolves at the back edge of the airfoil.

Interestingly, the creation of minute turbulence prevents the airfoil from stalling at low wind speeds.

Wind turbine blades are prone to stalling even at low wind speeds close to the root of the blade where the profiles are thick. On some of the newest rotor blades a stretch of about one meter along the back side of the blade near the root is supplemented with vortex generators.

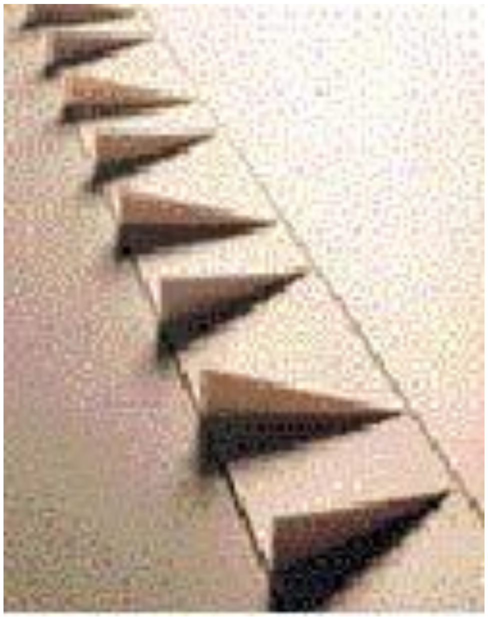

Figure 14. Vortex generators on airfoils.

TORQUE OVER SPEED

Current wind turbines designs favor rotor blade speed over torque. With large diameter rotor blades the tip speeds are approaching the sound speed generating undesirable flutter and hence noise.

Designs with lower blade speeds mean less stress on the blade as well as on the drive train and transmission. With lower kinetic energy content, the probability of ancillary damage would be lowered in the case of a blade failure.

While the current windmill designs incorporate features of propeller blades, emphasis must be switched to features of helicopter blades where torque is emphasized instead of speed. The proper application of torque has been applied in the design of the USA Hercules C-130J and the European A499M transport airplanes swept shape propellers, which are reported to reduce the drag. Such curved designs have also been used on submarine screws advocated to reduce cavitation and allow silent operation. The latter are being replaced with even more silent jet pumps.

Higher torque designs would allow wind turbines to start rotation at lower wind speeds than at their design cut-in wind speed. This is attained with a large blade area near the hub but can be enhanced with more sophisticated designs adopted from the wings of biplanes or triplanes which generated more lift than monoplanes. Such an alternative design may allow higher power turbines taking advantage of economies of scale, with lower hub height and cut-in wind speed.

Figure 15. Lockheed Hercules C130J swept blade propeller design.

Figure 16. Ship variable pitch propeller blade design.

Figure 17. Ohio class submarine silent screw, now replaced by ducted pump jets propulsion in Virginia class submarines. Source: Google Earth.

Figure 18. A499M European military transport plane swept propeller blades.

DISCUSSION

It must be noticed that as the wind speed increases, it is necessary for the rotor to speed up in order to remain near the optimal tip speed ratio. Unfortunately, this is in conflict with the requirements of most electrical generating systems, which require a constant generator frequency in order to supply electricity of a fixed frequency to the electrical power grid. As a consequence, a wind turbine which has a generator directly coupled to the electrical grid is compelled to operate for much of the time with a tip speed ratio which is not optimal.

An alternative is to decouple the generator from the grid by an intermediate system which facilitates variable speed operation. Manufacturers and researchers are producing variable speed turbines where the rotor speeds up with the wind velocity, in order to maintain a tip speed ratio near the optimal value. This wind turbine design uses an electronic control system using inverters and rectifiers electronics to stabilize the fluctuating voltage from the turbine before feeding it into the grid system.

EXERCISES

1. Use a plotting routine to show the profile of the available power flux in a wind stream as a function of the wind velocity, for a wind stream with 2.5 kW/m^2 at 16 m/s.

2. Use a plotting routine to show the profile of the available power flux in a wind stream as a function of the rotor diameter, for a wind turbine generating 600 kW at a 44 m rotor diameter.

3. Use Bernoulli's equation:

$$p_0 + \frac{1}{2}\rho_0 V_0^2 = p + \frac{1}{2}\rho V^2 = \text{constant},$$

to derive an expression for the pressure coefficient C_P for an aerodynamic body immersed in a free air stream with pressure p_0 and velocity V_0, at an arbitrary point in the flow where the pressure is p and the velocity is V.

4. The lift force on a rotor blade is described by the lift coefficient: $C_L = \frac{(L/A_L)}{\frac{1}{2}\rho V^2}$, and the drag force is described by the drag coefficient: $C_D = \frac{(D/A_D)}{\frac{1}{2}\rho V^2}$.

Derive the expression for the thrust coefficient C_T.

5. For an air density of 1.23 kg/m^3, a wind speed of 10 m/s, a rotor surface area of 10 m^2, and a rotor effective area in the drag direction of 5 m^2, estimate:

   1. The lift force L in Newtons,
   2. The drag force D,
   3. The thrust force T.

If the angle between the thrust and the incoming undisturbed air flow is 45 degrees, estimate:

   1. The perpendicular component of the force leading to translation of the rotor,
   2. The force parallel to the undisturbed air flow,
   3. The bending moment in the air stream on a *three* bladed turbine nacelle with a tower height of 50 meters.

Hint: $C_L = \frac{(L/A_L)}{\frac{1}{2}\rho V^2}$, $C_D = \frac{(D/A_D)}{\frac{1}{2}\rho V^2}$.

Use: Lift to drag ratio $C_L / C_D = 18$, Drag coefficient $C_D = 0.06$.

$$T^2 = L^2 + D^2$$

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