CHAPTER 1

INTRODUCTION

Wind-powered ships, grain mills, water pumps, and threshing machines all exemplify that extraction of power from wind is an ancient endeavor. With the evolution of mechanical insight and technology, the last decades of the 20th century, in particular, saw the development of machines which efficiently extract power from wind. "Wind turbine” is now being used as a generic term for machines with rotating blades that convert the kinetic energy of wind into useful power. The earlier wind turbine designs were driven by three basic philosophies for handling loads: (1) withstanding loads, (2) shedding or avoiding loads, and (3) managing loads mechanically, electrically, or both. In the midst of this evolution, many wind turbine designs saw the light of day, including horizontal axis and vertical axis turbines that spin about horizontal and vertical axes respectively. The turbines are equipped with one, two, three or multiple blades. Modern turbines evolved from the early designs, can be classified as two or three-bladed turbines with horizontal axes and upwind rotors.

Today, the choice between two or three-bladed wind turbines is merely a matter of a trade-off between aerodynamic efficiency, complexity, cost, noise and aesthetics. Additional design considerations can be included as wind climate, rotor type, generator type, load and noise minimization, and control approach. Moreover, current trends, driven by the operating regime and the market environment, involve development of low-cost, megawatt-scale turbines and lightweight turbine concepts. Whereas turbines operating at
constant rotor speed have been dominating up to now, turbines with variable rotor speed are becoming increasingly more common in an attempt to optimize the energy capture, lower the loads, obtain better power quality, and enable more advanced power control aspects. Utilization of renewable wind energy in India increases in many folds from the last decade of 20\textsuperscript{th} Century. Table 1.1 shows the installed capacity of wind turbine from various states of India and Figure 1.1 shows the wind energy map of India published by Center for Wind Energy Technology (CWET).

### Table 1.1 Installed capacities of Wind Turbine in India (CWET, India 2005)

<table>
<thead>
<tr>
<th>State</th>
<th>Installed Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhra Pradesh</td>
<td>9063</td>
</tr>
<tr>
<td>Gujarat</td>
<td>7362</td>
</tr>
<tr>
<td>Karnataka</td>
<td>7161</td>
</tr>
<tr>
<td>Kerala</td>
<td>1026</td>
</tr>
<tr>
<td>Madhya Pradesh</td>
<td>4978</td>
</tr>
<tr>
<td>Maharashtra</td>
<td>4519</td>
</tr>
<tr>
<td>Orissa</td>
<td>1520</td>
</tr>
<tr>
<td>Rajasthan</td>
<td>6672</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td>4159</td>
</tr>
<tr>
<td>West Bengal</td>
<td>32</td>
</tr>
</tbody>
</table>
Figure 1.1 Wind Energy Map of India

Courtesy: Center for Wind Energy Technology (CWET)
1.1 CONCEPTUAL ASPECTS IN WIND TURBINE

Some early wind turbine designs include multiple-bladed concepts as shown in Figure 1.2. These turbines are all characterized by rotors with high solidity, i.e. the exposed area of the blades is relatively large compared to the swept area of the rotor. A disadvantage of such a high-solidity rotor is the excessive forces that it will attract during extreme wind speeds such as in hurricanes (Mann 1998). To limit this undesirable effect of extreme winds and to increase efficiency, modern wind turbines are built with fewer, longer, and more slender blades, i.e. with a much smaller solidity. To compensate for the slenderness of the blades, modern turbines operate at high tip speeds.

![Multi blade wind turbine](image)

**Figure 1.2 Multi blade wind turbine**

1.1.1 Vertical Axis Turbines

Vertical axis wind turbines (VAWTs), such as the one shown in Figure 1.3 with C shaped blades, are among the types of turbine that have seen the light of day in the past century.
Classical water wheels allow the water to arrive tangentially to the water wheel at a right angle to the rotational axis of the wheel. Vertical axis wind turbines are designed to act correspondingly towards air.

Though, such a design would, in principle, work with a horizontal axis as well, it would require a more complex design, which would hardly be able to beat the efficiency of a propeller-type turbine. The major advantages of a vertical axis wind turbine illustrated in Figure 1.3, are that the generator and gearbox are placed on the ground and are easily accessible and yaw mechanism is not required. The disadvantages are an overall much lower level of efficiency, requirement of total dismantling just to replace the main bearing, and that the rotor is placed relatively close to the ground where the availability of wind is much less.

1.1.2 Horizontal Axis Turbines

Horizontal axis wind turbines (HAWTs), is the one shown in Figure 1.4, constitute the most common type of wind turbine in use today. In fact all grid connected commercial wind turbines are designed with propeller-
type rotors mounted on a horizontal axis on top of a vertical tower. In contrast to the mode of operation of the vertical axis turbines, the horizontal axis turbines need to be aligned with the direction of the wind, thereby allowing the wind to flow parallel to the axis of rotation.

As far as horizontal axis wind turbines are concerned, a distinction is made between upwind and downwind rotors. Upwind rotors face the wind in front of the vertical tower and have the advantage of somewhat avoiding the wind shade effect from the presence of the tower.

![Horizontal Axis Wind Turbine](image)

Figure 1.4 Horizontal Axis Wind Turbine

Upwind rotors need a yaw mechanism to keep the rotor axis aligned with the direction of the wind. Downwind rotors are placed on the back side of the tower so that the wind impinges on the blade after passing through the tower. A great disadvantage in this design is the fluctuations in the wind power due to the rotor passing through the wind shade of the tower which gives rise to more fatigue loads. Theoretically, downwind rotors can be built without a yaw mechanism, provided that the rotor and nacelle can be designed in such a way that the nacelle will follow the wind passively. This may, however, induce gyroscopic loads and hamper the possibility of unwinding the cables when the rotor has been yawing passively in the same direction for
a long time, thereby causing the power cables to twist. As regards large wind turbines, it is rather difficult to use slip rings or mechanical collectors to circumvent this problem. Whereas, upwind rotors need to be rather inflexible to keep the rotor blades clear of the tower, downwind rotors can be made more flexible. The latter implies possible savings with respect to weight and may contribute to reducing the loads on the tower. The vast majority of wind turbines in operation today have upwind rotors. The general arrangement of a typical horizontal axis wind turbine (HAWT) is shown in Figure 1.5.

![General arrangement of HAWT](image)

**Figure 1.5** General arrangement of HAWT
1.2 HISTORICAL BACKGROUND IN WIND POWER TURBINES

Brush is one of the founders of the American electrical industry. During the winter of 1887-88 Brush built what is today believed to be the first automatically operating wind turbine for electricity generation. After, Dane Poul la Cour, who later discovered that fast rotating wind turbines with few rotor blades are more efficient for electricity production than slow moving wind turbines. During World War II the Danish engineering company F.L. Smidth built a number of two- and three-bladed wind turbines. This three-bladed F.L. Smidth machine, built in 1942, looks more like a "Danish" machine. The innovative 200 kW Gedser wind turbine was built in 1956-57 by J. Juul for the electricity company SEAS at Gedser coast in the Southern part of Denmark. The Gedser wind turbine was refurbished in 1975 at the request of NASA which wanted measurement results from the turbine for the new U.S. wind energy programme. In 1979 they built two 630 kW wind turbines, one pitch controlled, and the other stall controlled. A carpenter, Christian Risager, however, built a small 22 kW wind turbine in his own back yard using the Gedser Wind Turbine design as a point of departure. The prototype of the NEG Micon 1500 kW Turbine was commissioned in September 1995. The prototype of the Vestas 1500 kW Turbine was commissioned in 1996. The megawatt market really took off in 1998.

The prototype of the NEG Micon 2 MW turbine was commissioned in August 1999. A tendering procedure for new offshore wind farms will be commenced in late 2003. Most of Horizontal axis wind turbines have a gearbox too, which turns the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity. Vertical axis wind turbines have the main rotor shaft running vertically. The advantages of this arrangement are that the generator and/or gearbox can be placed at the
bottom, near the ground, so the tower doesn't need to support it, and that the
turbine doesn't need to be pointed into the wind. Drawbacks are usually the
pulsating torque produced during each revolution; and the difficulty of
mounting vertical axis turbines on towers, meaning they must operate in the
slower, more turbulent air flow near the ground, with lower energy extraction
efficiency. The rotor and its three rotor blades constitute a rather flimsy
structure, consisting of cantilever-mounted blades on a central hub.
Nowadays, modern wind turbine engineers avoid building large machines
with an even number of rotor blades. The most important reason is the
stability of the turbine. A rotor with an odd number of rotor blades (and at
least three blades) can be considered to be similar to a disc when calculating
the dynamic properties of the machine. A rotor with an even number of blades
will give stability problems for a machine with a stiff structure. The reason is
that at the very moment when the uppermost blade bends backwards, because
it gets the maximum power from the wind, the lowermost blade passes into
the wind shade in front of the tower.

So, Most of the modern wind turbines are three-bladed designs with
the rotor position maintained upwind (on the windy side of the tower) using
electrical motors in their yaw mechanism. The design life time of modern
wind turbines is normally thought to be 20 years. The basic design aspects for
a rotor blade are the selection of material and shape. The material should be
stiff, strong, and light. The challenge for the designers is thus to go beyond
the simple plank and the shape of the blade with pre-twist into a design of the
blade structure that is optimized with respect to materials selection and cost-
effective production. Older style wind turbines were designed with wood,
steel, Aluminum materials. Nowadays, composite materials are extensively
used to design the wind turbine blades.
1.3 BLADES

Blades are the critical component in the wind turbine, since it is the actual energy converter. The blade profile is basically aerofoil in section. Various section of the blade made with its cross section and different kinds of load acting over it are shown in Figure 1.6. The first and most fundamental aerodynamic model developed for horizontal axis wind turbines, was the actuator disk theory proposed by Rankine in 1895. This highly idealized model treats the turbine rotor as a non-rotating homogeneous disc that removes energy available in the wind, and converts it into useful mechanical energy (Abbott et al 1959).

![Figure 1.6 Aerofoil wind turbine blade](image)

Using momentum theory, considering the pressure drop across the actuator, and by applying Bernoulli’s equation upstream and downstream of the disc it can be shown that the maximum possible power coefficient $C_{p_{\text{max}}}$ is 0.593. This value is called the Betz limit, and enables the maximum amount of power that a wind turbine can theoretically produce to be determined. This idealized flow theorem was further developed by Glauert, who treated the
rotor as a rotating actuator disk, and summed individual effects through a number of annulus stream-tubes. At this stage the effects of wake rotation had also been incorporated into the analysis to give a more accurate estimation of the power output. Glauert’s optimum actuator disk theory prompted the conception of Blade Element Theory, which further increased accuracy by integrating all properties over radial increments of the blades.

A section of a blade at radius \( r \) is illustrated in Figure 1.7, with the associated velocities, forces and angles shown. The relative wind vector at radius \( r \), denoted by \( W \), is the resultant of an axial component \( u_P \), and a rotational component \( u_T \). The rotational component is the sum of the velocity due to the blades motion, \( r\Omega \), and the swirl velocity of the air, \( \tau\Omega \). The axial velocity \( u_P \) is reduced by a component \( V_0p \), due to the wake effect or retardation imposed by the blades, where \( V_0 \) is the upstream undisturbed wind speed. The “t” and “p” terms represent the rotational and axial interference factors respectively. The angle of attack is denoted by \( \alpha \), the pitch of the blade by \( \phi \), and the angle of the relative wind to the plane of rotation, by \( \phi \). The resultant lift and drag forces are represented by \( F_L \) and \( F_D \), and directed perpendicular and parallel to the relative wind as shown.

Designing wind turbine blades using strip theory or related blade element theories requires knowledge of the characteristics and behaviour of airfoil sections. In the past, wind turbine designers have relied on airfoil sections and data intended for aircraft use. The NACA 23XX series, NACA 44XX series, and the NACA 63-2XX series airfoils are primarily for aircraft use, but have all been used extensively in the design of HAWTs. The NACA 44XX series has since proven to provide the best overall performance, and are almost insensitive to surface fouling. The increase in efficiency of modern wind turbine blades is a direct result of independent research into new sections specifically tailored for wind turbine blades. It is important to
remember that much of a turbine blade operates in the stalled region where the angle of attack is large, and low Reynolds number flows are experienced. Aircraft wings typically operate at lower angles of attack, and in extremely high Reynolds number flow regimes (Mann 1994).

**Figure 1.7** Blade force velocity diagram

**Figure 1.8** Variation of $C_L$ and $C_D$ with angle of attack
The characteristics of aerodynamic forces acting on bodies are commonly analysed by introducing non-dimensional form of the drag force and lift force, the drag coefficient \( C_D \) and lift coefficient \( C_L \) defined by:

\[
C_D = \frac{F_D}{\left(\frac{1}{2} \rho V^2 \right)(l)} \quad \text{and} \quad C_L = \frac{F_L}{\left(\frac{1}{2} \rho V^2 \right)(l)}
\]

The main parameter which determines the magnitudes of \( C_L \) and \( C_D \) is the angle of attack \( \alpha \). Therefore the basic way of describing the aerodynamic characteristics of an aerofoil section is to plot the variations \( C_L \) and \( C_D \) against \( \alpha \) and is shown in Figure 1.8. The lift coefficient increases almost linearly with angle of attack, until a maximum value is reached. During this range of angles, the flow around the aerofoil is approximately attached and the wake behind the body is very thin. Beyond this point, the flow separates well upstream of the trailing edge of the aerofoil to form a
large wake behind the body and the lift coefficient shows a sudden decline. This phenomenon is known as stalling and the angle of attack corresponds to the maximum lift is referred to as stall angle. For most of the aerofoil profiles commonly encountered in practice, the stall angle is in the range 15° to 25° and the maximum lift coefficient is in the range 1.1 to 1.3. The drag coefficient has a minimum value at a low lift coefficient and the variation shows approximately parabolic shape at angles of attack below stall. Beyond the stall angle, there is a sharp increase in the drag coefficient. A measure of the efficiency of the aerofoil as a lifting surface is given by lift to drag ratio $C_l/C_D$, which is also plotted in Figure 1.9. This ratio increases from zero at zero lift to a maximum value at a moderate lift coefficient, after which it decreases relatively slowly. The angle of attack corresponds to the maximum lift to drag ratio is referred to as optimum angle of attack, which is in the order of 3° for most of the common aerofoil shapes. The maximum lift to drag ratio is in the range 100 for NACA 24XX, 44XX and 64XX series whereas it is in the order of 40 for other profiles.

1.4 NACELLE

A typical nacelle in horizontal axis wind turbine consists of main shaft, gear box, brakes, yaw controller and generator is shown in Figure 1.10. The main shaft is one which transfers blade rotation to the generator. The main shaft is generally analysed in two segments namely low speed shaft and high speed shaft. The portion of the shaft between blade and gear box is termed as low speed shaft, since it rotates with lesser speed i.e. speed of the blade, in general in between 36 - 42 rpm. Portion of the shaft behind gear box is termed as high speed shaft which rotates with rated speed of the generator in the order of 1500 rpm. Purpose of the gear box is to increase the speed of main shaft from blade speed to rated speed of the generator. The speed ratio of the gear box is usually in the order of 1:40, hence a multi stage gear box
consisting of planetary stage with helical stage is employed. Brakes are employed to arrest the rotation of main shaft in case of overload or system failure. Purpose of the yaw controller is to rotate the nacelle to align with the direction of wind. Function of this yaw motor is mainly microprocessor controlled. Wind vane, which is connected to the nacelle arrangement gives the signal to the yaw control mechanism. Wind vane senses the change of the direction of the wind. The generator circuit consists of an alternator, motor, electromagnetic clutch and an ac solenoid braking with control circuit. The purpose of the control circuit is to provide initial torque to the blade through alternator using the motor, electromagnetic clutch and a velocity sensor. Second purpose of the control circuit is to apply brake when the speed of the alternator exceeds beyond its rated speed. Velocity sensor receives the signal from anemometer which measures the wind velocity and is also connected to the nacelle arrangement.

Figure 1.10  Exploded view of a Nacelle
1.5 TOWER

The tower of a wind turbine supports the nacelle and the rotor and provides the necessary elevation of the rotor to keep it clear off the ground and bring it up to the level where the wind resources are available. The towers for large wind turbines are typically made of steel, but concrete towers are sometimes used. Nowadays, most towers are tubular towers, however, lattice towers are also in use. Guyed towers are used for relatively small wind turbines only. The tower is usually connected to its supporting foundation by means of a bolted flange connection or a weld. In the context of wind turbines, the tower constitutes a low-technology component whose design is easy to optimize. This may come in useful as the cost of a tower usually forms a significant part of the total cost of a wind turbine. Various types of Wind turbine towers are shown in Figure 1.11.

![Gay Wired](image1)  ![Lattice](image2)  ![Tubular](image3)

Figure 1.11 Various Types of Towers
1.5.1 Tubular Towers

Most large wind turbines are delivered with tubular steel towers, which are manufactured in sections of 20-30 m length with flanges at either end. The sections are bolted together on the site. The towers are conical, i.e. their diameters increase towards the base, thereby increasing their strength towards the tower base, where it is needed the most, because this is where the load response owing to the wind loading is the largest. Since the necessary shell thickness is reduced when the diameter increases, the conical shape allows for saving on the material consumption. An advantage of tubular towers compared to other towers is that they are safer and more comfortable for service personnel unlike the others in which the personnel have to enter and climb the towers.

1.5.2 Lattice Towers

Lattice towers are manufactured by means of using welded steel profiles or L-section steel profiles. Since a lattice tower requires only about half as much material as a freely standing tubular tower with a similar stiffness. The basic advantage of lattice towers is reduction of cost. It also gives less wind shade than a massive tower. The major disadvantage of lattice towers is their visual appearance, although this is a debatable issue. Nevertheless, for aesthetic reasons lattice towers have almost disappeared from use for large, modern wind turbines.

1.5.3 Guyed Pole Towers

Many small wind turbines are built with narrow pole towers supported by guy wires. The advantage is weight savings and thereby reduced costs. The disadvantages include difficult access around the towers, which
make them less suitable in farm areas. Finally, this type of tower is more prone to vandalism, thus compromising the overall safety.

1.6 LOAD TYPES

The external loads acting on a wind turbine are mainly wind loads. As a wind turbine consists of slender elements such as blades and tower, inertia loads will be generated in addition to the gravity loads that act on these elements (Fitzwater 2001). Loads due to operation such as centrifugal forces, Coriolis forces and gyroscopic forces must also be considered. In most cases, the loads on a wind turbine can thus be classified as follows (Larsen and Sorensen 1996):

- Aerodynamic blade loads
- Gravity loads on the rotor blades
- Centrifugal forces and Coriolis forces due to rotation
- Gyroscopic loads due to yawing
- Aerodynamic drag forces on tower and nacelle
- Gravity loads on tower and nacelle

1.6.1 Centrifugal, Inertia and Gravity Loads

The inertia and gravity loads on the rotor are mass dependent loads. The cross-sectional centrifugal force $F_c$ depends on the angular rotor speed, the radial position, and the mass of each blade element. At the blade root, this force is

$$F_c = \sum_{i=1}^{n} m_i r_i \omega^2$$  \hspace{1cm} (1.2)
Here $m_i$ is the mass of the i’th blade and $r_i$ is the radial position of the i’th blade under consideration and $\omega$ is the angular velocity of blade rotation.

The gravity force is simply given as

$$F_G = \sum_{i=1}^{n} m_i g v = m_{\text{blade}} g$$

(1.3)

Here $g$ is the acceleration due to gravity and $m_{\text{blade}}$ is the total mass of the blade.

1.6.2 Gyroscopic Loads

In general, gyroscopic loads on the rotor will occur for any flexible rotor support. In particular, gyroscopic loads on the rotor will occur whenever the turbine is yawing during operation. This will happen regardless of the structural flexibility and will lead to a yaw moment $M_K$ about the vertical axis and a tilt moment $M_G$ about a horizontal axis in the rotor plane. For a three-bladed rotor, the net resulting yaw moment due to the gyroscopic load effects is zero, $M_K = 0$, whereas a non-zero constant tilt moment is produced, $M_G = \frac{3M_0}{2}$, in which

$$M_0 = 2\omega \omega_k \sum_{i=1}^{n} m_i r_i^2$$

(1.4)

where $\omega$ is the angular velocity of the rotor and $\omega_k$ is the angular yaw velocity.
For a two-bladed rotor, the gyroscopic load effects lead to a cyclic yaw moment and a cyclic tilt moment. The magnitude of $M_K$ and $M_G$ for this case is as follows:

$$M_K = 2M_0 \cos(\omega t) \sin(\omega t)$$

$$M_G = 2M_0 \cos^2(\omega t)$$ (1.5) (1.6)

In many cases it is possible to neglect gyroscopic effects, because the angular velocity of the yaw system is usually rather small. However, flexible rotor-bearing supports can lead to significant gyroscopic forces (rotor whirl), and gyroscopic forces should never be neglected for present MW turbines.

### 1.6.3 Aerodynamic Loads

The true wind flow in the vicinity of the wind turbine rotor is rather complex, because the rotor induces velocities. Hence it is common practice to use a simplified method for calculating rotor loads to be used for a wind turbine design. The wind velocity conditions at a blade cross-section are illustrated in Figure 1.7. Using equation (1.1), the aerodynamic forces on the blade, viz. a lift force and drag force can be computed using the following expressions.

Lift force, $F_L = C_L \left( \frac{1}{2} \rho_a V^2 \right) c l$ (1.7)

Drag force, $F_D = C_D \left( \frac{1}{2} \rho_a V^2 \right) c l$ (1.8)
The aerodynamic drag force, $F_{D}^{1}$ on the tower and the nacelle can be calculated on the basis of the projected area perpendicular to the flow

$$F_{D}^{1} = 0.5 \rho_{w} A V^{2} C_{D}$$  \hspace{1cm} (1.9)

$C_{D}$ aerodynamic drag coefficient and $A$ is projected area of tower and nacelle perpendicular to the flow.

The normal force and tangential force per length unit of the blade is

$$F_{N} = \frac{1}{2} \rho \frac{V^{2} (1 - p)^{2}}{\sin^{2} \varphi} c C_{N}$$  \hspace{1cm} (1.10)

$$F_{T} = \frac{1}{2} \rho \frac{V (1 - p) \omega r (1 + t) c C_{T}}{\sin \varphi \cos \varphi}$$  \hspace{1cm} (1.11)

Constants $p$ and $t$ are the axial induction factor and tangential induction factor respectively and can be found using Glauert’s correction. $C_{N}$ and $C_{T}$ are the normal and tangential coefficients.

$$p = \frac{1}{2} \left( 2 + K (1 - 2 p_{c}) - \sqrt{(K (1 - 2 p_{c}) + 2)^{2} + 4 \left( K p_{c}^{2} - 1 \right) } \right)$$  \hspace{1cm} (1.12)

Here $K = \frac{4 F \sin^{2} \varphi}{\sigma C_{N}}$ and $p_{c} = 0.2$  \hspace{1cm} (1.13)

$$t = \frac{1}{\left( \frac{4 F \sin \varphi \cos \varphi}{\sigma C_{T}} - 1 \right)}.$$  \hspace{1cm} (1.14)
Here \[ F = \frac{2}{\pi} \arccos \left( \exp \left( -\frac{B}{2} \frac{R-r}{r \sin \phi} \right) \right) \] (1.15)

\( R \) is the rotor radius. Note that \( F \) is known as Prandtl’s tip loss factor. The solidity \( \sigma \) is defined as the fraction of the cross-sectional area of the annular element which is covered by the blades (Guidelines for Design of Wind Turbines, 2002). The solidity depends on the radius \( r \) of the annular element and can be found as

\[ \sigma(r) = \frac{c(r)B}{2\pi r} \] (1.16)

in which \( B \) denotes the number of blades.

### 1.7 SELECTION OF BLADE MATERIALS

A material is that out of which anything is or may be made. Much number of factors are affecting for the material selection. They are properties of materials, performance requirements, material’s reliability, safety, physical attributes, environmental conditions, availability, disposability, recyclability, and finally economic factors. Among these properties,

1. One of the most important factors affecting selection of materials for engineering design is the properties of the materials. The important properties of the materials are mechanical, thermal, chemical properties, etc.

2. The material of which a part is composed must be capable of performing a part’s function (always it must be possible or not) with out failure.
3. A material in a given application must also be reliable.

4. A material must safely perform its function.

5. Physical attributes such as configuration, size, weight, and appearance sometimes also serve functional requirements can be used.

6. The environment in which a product operates strongly influences service performance.

7. A material must be readily available, and available in large enough quantity, for the intended application.

8. The cost of the materials and the cost of processing the materials into the product or part. The development and manufacture of satisfactory products at minimum cost is to make a sound, economic choice of materials.

The material selection process involves the following major operations:

- Analysis of the materials application problem.
- Translation of the materials application requirements to materials property values.
- Selection of candidate materials.
- Evaluation of the candidate materials.

And in any material selection, the following requirements are focused. They are

1. High material stiffness is needed to maintain optimal shape of performance.
2. Low density is needed to reduce gravity forces,
3. Long-fatigue life is needed to reduce material degradation.

The optimal design of the rotor blades is today a complex and multifaceted task and requires optimization of properties, performance, and economy.

1.8 BLADE MATERIALS

Wind energy is captured by the rotation of the wind turbine's rotor blades. Rotor blades have historically been made of wood, but because of its sensitivity to moisture and processing costs modern materials such as glass fiber reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP), steel and aluminum are replacing the traditional wooden units. Wood is a composite of cellulose and lignin. Wood finds many engineering applications and has long been a common construction material. Woods are potentially interesting because of their low density, but their rather low stiffness makes it difficult to limit the (elastic) deflections for very large rotor blades. Even wood materials with cellulosic fibers all aligned in the major load-bearing directions are close to the maximum performance possible for wood. Furthermore, wood is a natural material and thus environmentally attractive, but at the same time difficult to obtain in reproducible and high quality, which is a requirement for stable and economical manufacturing of rotor blades and thus economically attractive wind energy. Steel is an alloy of iron and carbon. Older style wind turbines were designed with heavier steel blades or nickel alloy steels which have higher inertia, and rotated at speeds governed by the AC frequency of the power lines. The high inertia buffered the changes in rotation speed and thus made power output more stable. The purpose of nickel alloy lessens distortion in quenching and lowers the critical temperatures of steel and widens the range of successful heat treatment. Nickel alloy
possesses good corrosion and oxidation resistance. Alloy steel was once thought to be an optimum choice for blade fabrication, but was soon abandoned because of its high weight and low fatigue level.

Aluminium is a silvery white metal with a density about one third that of steel. Aluminum was only implemented in testing situations because it was found to have a lower fatigue level than steel. Aluminium is ductile and good heat conductor. Aluminium is a low price metal but it has good reliability and has a low tensile strength. Aluminum is lightweight, but weaker and less stiff than steel. The fibers and the matrix materials like polyesters, vinyl esters, epoxies etc., are combined into the composites. These composites have good properties like mechanical, thermal and chemical properties. Firstly, the glass fibers are amorphous with isotropic properties. Most glass-reinforced products are made with E-glass (electrical glass), which has good electrical and mechanical properties and high heat resistance. E-glass is available as chopped fiber, milled fiber, continuous roving, woven roving, woven fabric, and reinforcing mat. Glass fibers for composites have good properties like moderate stiffness, high strength, and moderate density.

Carbon fibers are composed of nearly pure carbon, which forms a crystallographic lattice with a hexagonal shape called graphite. In recent years carbon fibers are of increasing interest because of the requirements presented by the ever-larger rotor blades and the decreasing price of carbon fibers. Carbon fibers for composites have an excellent combination of very high stiffness, high strength, light weight and low density.

1.9 BLADE PROFILE

Streamlined body shapes are used in many fluid dynamic applications with the objectives of generating lift force and/or reducing drag force (pressure drag). Some of the applications include aircrafts, ground
vehicles, fluid machinery such as fans, pumps, propellers, wind turbine rotors, etc. and water crafts like boats, ships, submarines. The widely used streamlined body shape in such applications is the aerofoil, which has a rounded nose and a sharp trailing edge (Christian et al 2002). Flow around such aerofoil under normal operating configurations (i.e. align to the flow) is attached and there is no flow separation and formation of large wake, even at high Reynolds numbers. Therefore the pressure drag is almost zero and the main contribution to the drag is from frictional drag, which is also very small. If the flow is not symmetric, there is a lift force acting on the body. Generation of this lift force is associated with formation of circulation around the aerofoil due to its basic shape. Let an aerofoil is instantaneously placed in a steady uniform flow with small angle of attack. The initial flow pattern takes the form that corresponds to ideal flow in which there are two stagnation points, as shown in Figure 1.12(a).

The stagnation point near the trailing edge is on the top surface, which requires the fluid flowing along the underside of the aerofoil to turn sharply around the trailing edge. Theoretically such motion would create an infinite velocity at the trailing edge, which is not a problem in ideal fluid flow. However, in real fluid, infinite velocities are inadmissible and the flow will adjust itself so that the stagnation point moves to the trailing edge and hence removes the singular point (this is known as Kutta-Joukowsky Hypothesis). The reason for above behaviour is that, in real fluid, the fluid particles undergo dissipation of energy due to viscous friction and therefore have insufficient energy to take the turn at the trailing edge, and therefore breakaway from the surface. This also causes fluid on upper surface to move from the stagnation point towards the trailing edge, thus forming an eddy known as starting vortex, as shown in Figure 1.12(b). The starting vortex generates an equal and opposite circulation around the aerofoil (Figure 1.12(c)). The starting vortex is rapidly washed away from the aerofoil,
but maintains a circulation around the aerofoil (see Figure 1.12(d)). The value of circulation around the aerofoil is just that necessary to shift the stagnation point to the trailing edge (Panofsky et al 1984). Under these circumstances, the pressure distributions on the upper and lower surfaces are different, as shown in Figure 1.13, and result in a high lift force.

Figure 1.12 Circulation around aerofoil

Figure 1.13 Pressure distribution around aerofoil
1.10  NACA FOUR-DIGIT SERIES

The first family of airfoils designed using this approach was known as the
NACA Four-Digit Series. The first digit specifies the maximum camber (m)
in percentage of the chord (airfoil length), the second indicates the position of
the maximum camber (g) in tenths of chord, and the last two numbers provide
the maximum thickness (h) of the airfoil in percentage of chord. For example,
the NACA 4412 airfoil has a maximum thickness of 12% with a camber of
4% located 40% back from the airfoil leading edge (or 0.4c). Utilizing these
m, g, and h values, we can compute the coordinates for an entire airfoil using
the following relationships:

1. Pick values of x from 0 to the maximum chord c.
2. Compute the mean camber line coordinates by plugging the
   values of m and g into the following equations for each of the
   x coordinates.

\[
\text{From } x=0 \text{ to } x=g; \quad y_c = \frac{m}{g^2} \left(2gx - x^2\right) \quad (1.17)
\]

\[
\text{From } x=g \text{ to } x=c; \quad y_c = \frac{m}{(1-g)^2} \left[(1-2g) + 2gx - x^2\right] \quad (1.18)
\]

In the above equations, \( x \) = coordinates along the length of the
airfoil, \( y \) = coordinates above and below the line extending along
the length of the airfoil.

3. Calculate the thickness distribution above (+) and below (-)
   the mean line by plugging the value of h into the following
   equation for each of the x coordinates.

\[
\pm y_h = \frac{h}{0.2} \left(0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right) \quad (1.19)
\]
4. Determine the final coordinates for the airfoil upper surface
\((x_U, y_U)\) and lower surface \((x_L, y_L)\) using the following
relationships.

\[
\begin{align*}
    x_U &= x - y_h \sin \theta ; \\
    y_U &= y_c + y_h \cos \theta ; \\
    x_L &= x + y_h \sin \theta ; \\
    y_L &= y_c - y_h \cos \theta ,
\end{align*}
\]

\[
\theta = \tan^{-1} \left( \frac{dy_c}{dx} \right)
\]

Using the above procedure, final coordinate point for a typical
NACA 4412 profile having a chord length of 300 mm is generated and is
shown in Table 1.2.

### Table 1.2 Coordinates of NACA 4412 profile

<table>
<thead>
<tr>
<th>Point</th>
<th>Coordinate</th>
<th>Point</th>
<th>Coordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>300.0501</td>
<td>0.3747</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>298.8885</td>
<td>0.6960</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>295.4205</td>
<td>1.6443</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>289.6938</td>
<td>3.1737</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>281.7888</td>
<td>5.2116</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>271.8177</td>
<td>7.6641</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>259.9248</td>
<td>10.4214</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>246.2844</td>
<td>13.3653</td>
<td>33</td>
</tr>
<tr>
<td>9</td>
<td>231.1005</td>
<td>16.3734</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>214.6029</td>
<td>19.3233</td>
<td>35</td>
</tr>
<tr>
<td>11</td>
<td>197.0457</td>
<td>22.0965</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>178.7025</td>
<td>24.5814</td>
<td>37</td>
</tr>
<tr>
<td>13</td>
<td>159.8640</td>
<td>26.6742</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td>140.8320</td>
<td>28.2843</td>
<td>39</td>
</tr>
<tr>
<td>15</td>
<td>121.9170</td>
<td>29.3355</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>103.1604</td>
<td>29.6430</td>
<td>41</td>
</tr>
<tr>
<td>17</td>
<td>85.1190</td>
<td>29.0097</td>
<td>42</td>
</tr>
<tr>
<td>18</td>
<td>68.1486</td>
<td>27.4833</td>
<td>43</td>
</tr>
<tr>
<td>19</td>
<td>52.5549</td>
<td>25.1607</td>
<td>44</td>
</tr>
<tr>
<td>20</td>
<td>38.6148</td>
<td>22.1781</td>
<td>45</td>
</tr>
<tr>
<td>21</td>
<td>26.5680</td>
<td>18.7029</td>
<td>46</td>
</tr>
<tr>
<td>22</td>
<td>16.6107</td>
<td>14.9184</td>
<td>47</td>
</tr>
<tr>
<td>23</td>
<td>8.8926</td>
<td>11.0076</td>
<td>48</td>
</tr>
<tr>
<td>24</td>
<td>3.5187</td>
<td>7.1367</td>
<td>49</td>
</tr>
<tr>
<td>25</td>
<td>0.5484</td>
<td>3.4383</td>
<td>50</td>
</tr>
</tbody>
</table>