Introduction:

Propeller is an interface between an aircraft engine and an aircraft. A typical propeller blade would have **a leading edge and a trailing edge**. Propeller blades are essentially made up of air foils, which invariably then participate in the creation of thrust. The root of the propeller is shaped in such a manner that it blends with the hub.

The **root** is almost a circular section, sacrificing all the airfoil shapes, essentially to provide good structural strength to the blade. Propeller blade, when in rotation, is actually a like a cantilever beam.

The **tip of the propeller** quite often is very thin, often may not make a very large contribution to the thrust creation. The tip is rounded essentially for reducing the losses related to the tip flow, the flow around the tip.

The propellers are finally rotating around central shaft, which is the hub of the engine and this shaft is getting power from the engine as necessitated by the actual propeller rotation.

Propeller blade

The common feature in aerofoils of propellers is that they have flat under surface. There is a rounding around the leading edge of a typical airfoil. The cambered side is the main lift producing surface of this propeller. The airfoil always ends with a trailing edge, with a small rounding to reduce various frictional loss.
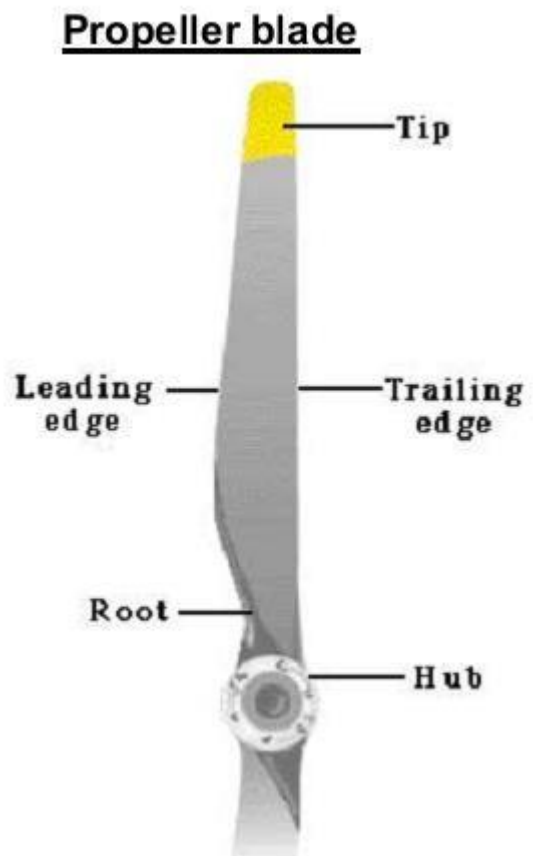
Blade Shaping:
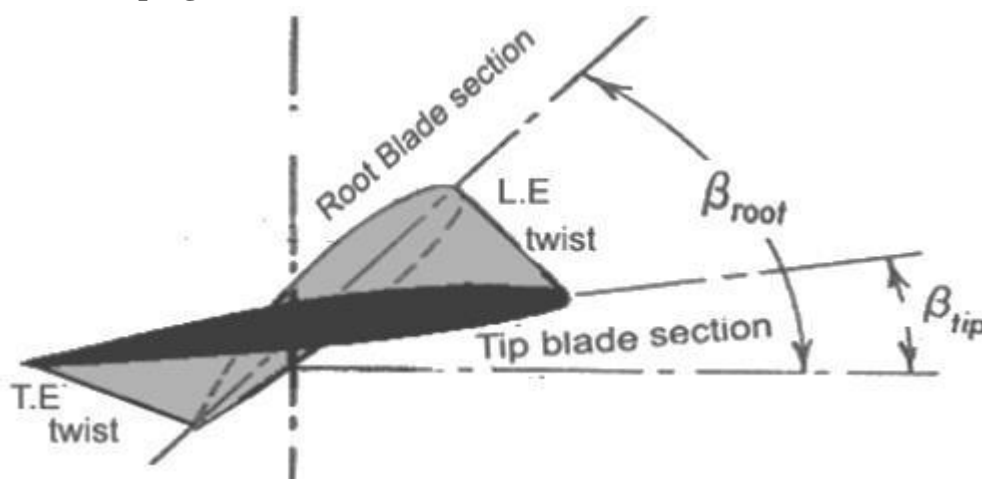
Typically when a blade is operational, the lift creation depends on the way the flow is locally incident on the airfoil. It depends on the airfoil characteristic, which is often decided by the local angle of attack. The root section of the blade, it is subtending a very high angle of blade setting On the other hand, near the tip of the blade section, it is set at a low angle.

These blade elements are stacked, from root to the tip of the blade. This root to tip stacking essentially creates local flow incidents at various stations or various sections of the blade.

For efficient operation of each of these blade elements, which are airfoils, there is aneed to create an appropriate angle of attack. There is maximum angle of attack, where this airfoil is likely to stall;

Propeller blade local flow details:
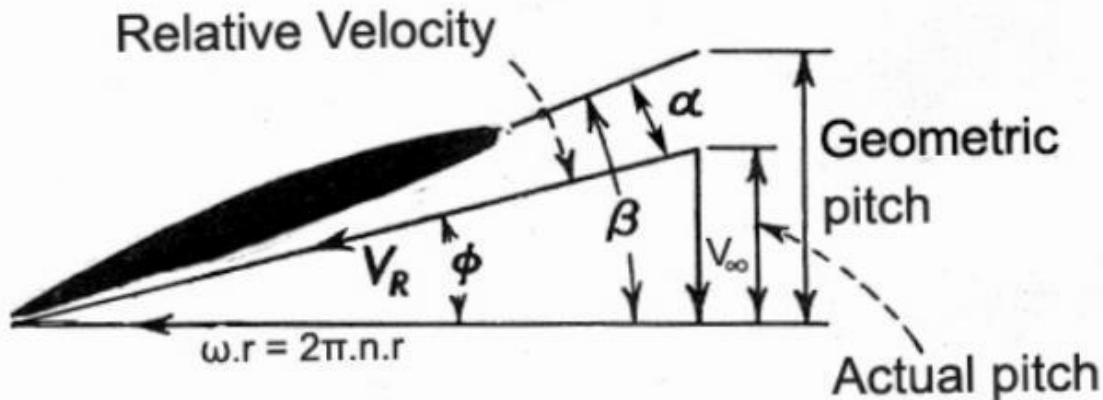
Consider a typical propeller blade, which is a airfoil section. When a propeller is rotating. The **rotation provides a certain rotational speed** of the particular blade section, so each blade section is now rotating at a particular rotational speed called a tangential velocity(ωr). where ω is angular velocity, $2\pi n$ being the rpm of the blade, r is the radius of the particular section from the axis of rotation of the propeller.

If the aircraft is moving forward, it has a forward velocity, V_∞, it creates an angle of ϕbetween the two velocities - the rotational velocity and the forward velocity, then it creates a resultant velocity V_R, which is now the relative incident flow on to this airfoil section. This incident flow now creates an angle of attack of alpha with reference to airfoil section.

If angle of attack has a maximum - beyond which this airfoil will refuse to do any aerodynamic action and a very low angles of attack or negative angles of attack also could start creating non-aerodynamic effects of the propeller.

Geometric Pitch is the theoretical distance a propeller would advance in one revolution.

Actual Pitch is the actual distance a propeller advances in one revolution in the air.

Mechanism of Creation of Thrust by Propellers:
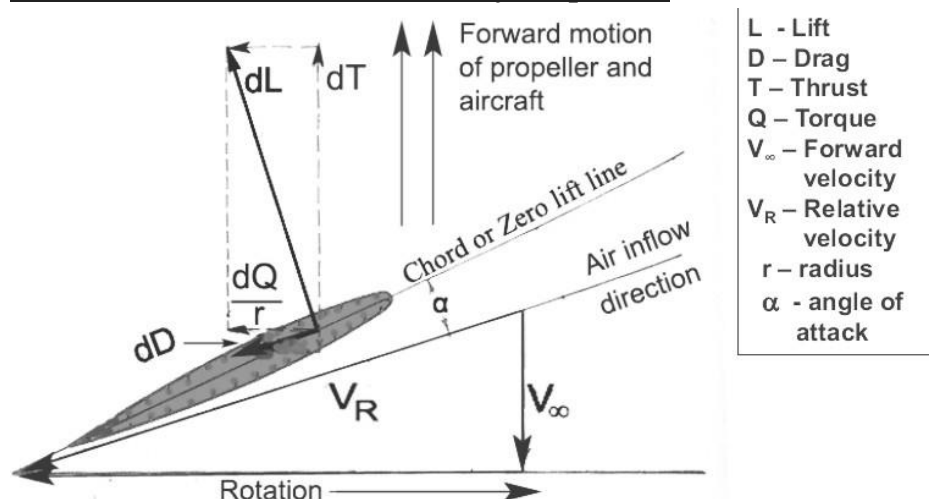
Consider a particular blade section which is creating a lift and experiencing a drag. This lift and drag, which are perpendicular and parallel to the chord, can be decomposed into axial force and the tangential force (dQ / r). dT is the elemental thrust of this particular blade section, dQ by r is the elemental tangential force, which has to be met by the supply of the torque from the engine. So, this is the component that the engine needs to supply for creation of this thrust, through the shape of this propeller blade section, which is an airfoil section. This is the aerodynamic mechanism by which the thrust is created by the propellers, where airfoil shape is the fundamental element in the creation of thrust.

Different types of Pitch setting arrangements.
- A **fixed pitch propeller**, in which the geometric pitch cannot be varied, must be matched to the various operating conditions of the engine and of the aircraft.
- A **variable pitch propeller**, either variable manually, or through hydro-mechanical control system, usually offer at least two or more blade settings, one fine and the other coarse, to maximize the propeller efficiency, during take-off and during cruise respectively.
- **A constant speed propeller**---automatically changes propeller pitch according to a built in control law (floating pitch) so as to maintain proper torque such that the speed of the propeller shaft is maintained constant with the help of a governor and a electro-hydro-mechanical control system. Most modern propellers are constant speed propellers

Propeller performance parameters:

Advance ratio: J the *advance ratio* is the ratio of the free stream fluid speed to the propeller cyclorotor tip speed. When a propeller-driven vehicle is moving at high speed relative to the fluid, or the propeller is rotating slowly, the advance ratio of its propeller(s) is a high number; and when it is moving at low speed, or the propeller is rotating at high speed, the advance ratio.The advance ratio J is a non-dimensional term given by

$$J = V_\infty / (n.D)$$

V_∞ is the free stream fluid velocity, typically the true airspeed of the aircraft or the water speed of the vessel
n is the rotor rotational speed
r is the rotor radius.

The propeller efficiency: The propeller efficiency is given by the usual output power to input power ratio,

$$\eta_P = (T.V_\infty)/P = (T.V_\infty)/(2.\pi.n.Q)$$

Propeller tip speed: The propeller tip speed is given by

$$V_{tip,\ helical} = \sqrt{(\{\pi\ nD\}^2 + V_\infty^2)}$$

When propeller starts rotating at high speed. The propellers would experience tip speeds, which are supersonic and then you would have shocks. Those shocks would then reduce the efficiency of the propellers, the propellers could become of lower efficiency
- Metal propellers are limited to M_{tip} of 0.85,
- Wooden ones are limited to M_{tip} of 0.75

Propeller Theories: There are two classical approaches to propeller theory
1) Momentum Theory
2) Blade Element Theory

Momentum Theory:

The actuator disk theory replaces the propeller with an infinitely thin "actuator" disk, which imparts a certain momentum to the fluid passing through it, thus produces an increase in axial velocity and axial momentum This theory provides an initial idea regarding the performance of a propeller but fails to furnish the required design data for the propeller blades
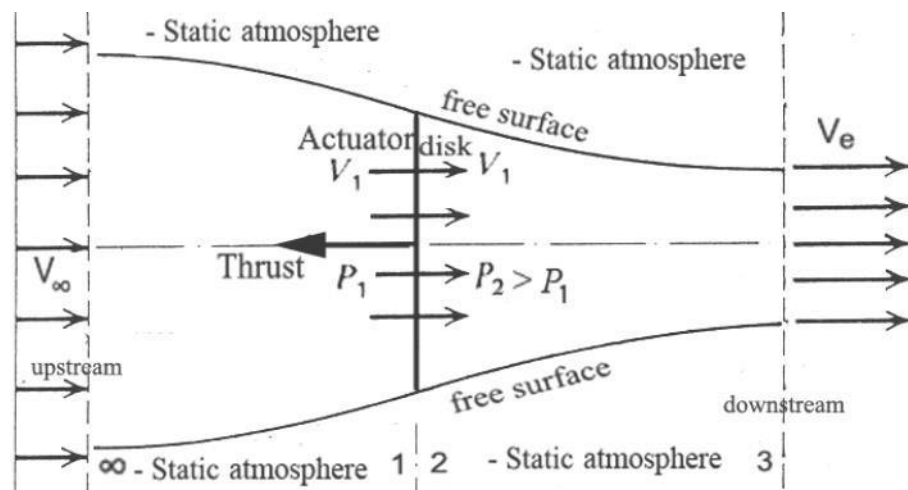
Assumptions for conceptual modelling of a propeller:

- The propeller is assumed to be replaced by an actuator disk a flow energizer.
- The 'disk' is assumed to be of very small thickness and is a continuous and 100% porous body of no mass, with a projected frontal area 'A' (swept area) equal to the annulus of the rotating propeller blades.
- There is no 'resistance' (i.e. drag) of the air passing through the 'actuator disk'.
- The axial velocity, V1 through the 'disk' is uniform over the 'actuation' area and is considered to be smooth across the disk i.e. no abrupt changes are 'experienced'.
- The received energy manifests itself in the working medium (i.e. air) finally in the form of differential pressure (p2–p1).uniformly distributed across the disk surface.
- The fluid medium, air, is a assumed to be a perfect incompressible fluid. Flow is assumed 'irrotational' in front of and behind the disk, but not through it.
- The static pressures far from the disk, i.e. far upstream and far downstream, are both assumed equal to the atmospheric pressure. The corresponding velocities are independent values, to be determined separately.

The mass flow through the disk from continuity, is

$$\acute{m} = \rho.A.V \dots\dots\dots\dots\dots\dots\dots 1$$

The thrust produced by the disk from Newton's II and III laws resulting in reaction force, thrust.

$$T = \acute{m}.\partial V = \rho.A.V.(V_e - V_\infty)\dots\dots\dots\dots\dots 2$$

From simple fluid statics, thrust is produced by the differential static pressure on either side of the disk ,multiplied by its surface area (swept area)

$$T = A\ (P_2 - P_1) \dots\dots\dots\dots\dots\dots\dots\dots\ 3$$

Applying Bernoulli's equation on either side of the dis

$$P_\infty + \tfrac{1}{2}\rho\ V_\infty{}^2 = P_1 + \tfrac{1}{2}\rho\ V_1{}^2 - \text{upstream} \dots\dots\dots\dots\dots\dots\dots\ 4$$

$$P_2 + \tfrac{1}{2}\rho\ V_2{}^2 = P_\infty + \tfrac{1}{2}\rho\ V_e{}^2 - \text{downstream} \dots\dots\dots\dots\dots\dots 5$$

Using, $V_1 = V_2 = $ constant through the disk,

$$P_2 - P_1 = \tfrac{1}{2}.\rho.\ (V_e{}^2 - V_\infty{}^2) \dots\dots\dots\dots\dots\dots\dots\dots\ 6$$

Useing equations 2,3,6

$$V_1 = \tfrac{1}{2}.(V_e + V_\infty) \dots\dots\dots\dots\dots\dots\dots\dots\ 7$$

This simple analysis shows that the air flow velocity through the actuator disk is the mean of the velocities far upstream and far downstream of the propeller.

$$\text{Thus thrust } T = \tfrac{1}{2}.\rho.(V_e{}^2 - V_\infty{}^2) \dots\dots\dots\dots\dots\dots\ 8$$

The velocity at the disk comes out to be the free stream axial velocity,

$$V_1 = V_\infty + v ; \quad \text{and } V_e = V_\infty + 2.v \dots\dots\dots\dots\dots\dots\ 9$$

$$\text{Therefore, } T = \rho\ A\ (V_\infty + v)\ 2.v \dots\dots\dots\dots\dots\ 10$$

From the equation the *induced velocity*, *v*, can be found as,

$$v = \frac{[-V_\infty + \sqrt{\{V_\infty^2 - (2T/\rho.A)\}}]}{2} \quad \dots\dots\dots\dots 11$$

<u>For a static thrust</u>, where the propeller is not in forward motion (at take off), $V_\infty = $ zero,

$$v = \sqrt{\frac{T}{2\ \rho.A}} \quad \dots\dots\dots\dots\dots\dots\dots\dots 12$$

The ideal efficiency can be calculated by using classical definition of eficiency ,

$$\eta p = Pout\ /\ Pin \dots\dots\dots\dots\dots\dots\dots\ 13$$

$$P_{out} = T\ V_\infty \text{ and } \quad P_{in} = T\ V_1 \dots\dots\dots\dots 14$$

$$\text{Therefore, } \quad \eta_i = Pout\ /\ P_{in}$$

$$= T.V_\infty\ /\ T.V_1$$

$$= V_\infty\ /\ [\tfrac{1}{2}(V_\infty + V_e)]$$

$$= 2V_\infty\ /\ (V_e + V_\infty) \dots\dots\dots\dots\dots\dots 15$$

Blade Element Theory.

Blade element theory is another approach proposed to study the aerodynamic design and performance of propellers. The foundation of this theory is found in the classical airfoil and wing theory. A propeller is a spinning (twisted) wing, with angular speed ω=2πn with its span-wise elements in solid-body rotation. The rotational speed increases linearly with distance from the axis of rotation, r, hence the need for twist. Therefore, by virtue of rotation, the blade sections are subjected to relative flow magnitude and angle, that is, as seen by the blade element. A propeller blade is composed of airfoil sections along its span that see the relative flow and create local aerodynamic forces and torques. The aerodynamic performance of the sections depends on the local relative flow speed, airfoil profile, and angle of attack and Reynolds number based on chord and relative speed. The sketch that shows a propeller and its sectional velocity vectors and angles with elemental aerodynamic force components.
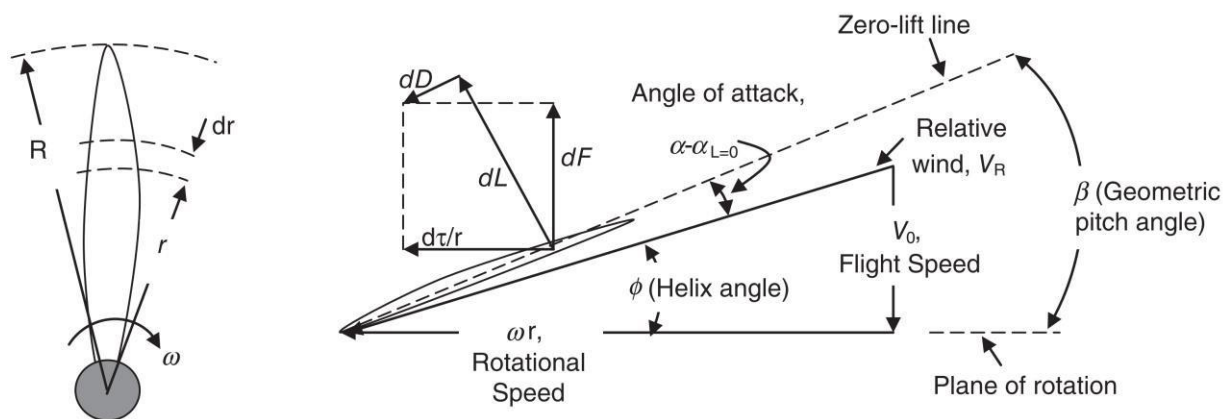
The relative flow, or the relative wind VR, is created as the vector sum of flight and the blade rotational speed at any element along the span. The relative flow angle is φ which is also called the helix angle.

The aerodynamic lift on the blade element is proportional to the local effective angle of attack, which is composed of:

- The geometric angle of attack;
- The angle-of-zero lift (due to airfoil camber)
- The induced angle of attack (due to the trailing vortices in the propeller wake).

The basic blade element theory, however, does not account for the induced angle of attack that is caused by the 3D trailing vortices. Therefore, in the strict sense, propeller blade performance in three dimensions is constructed from the superposition of sectional 2D performance. The geometric pitch angle,β is also shown in Figure; it is the angle that the blade element (in cambered airfoil measured from zero-lift-line) makes with respect to plane of rotation. The tangential force element multiplied by the moment arm, r, measured from the axis of rotation, creates blade element torque, dr as shown in Figure. The propeller parameters of interest, namely thrust and torque, are the integrals of elemental thrust and torque along the blade span. In turn, the elemental torque and thrust are related to the lift and drag components, using the pitch angle, φ

$$dF = dL \cos \phi - dD \sin \phi$$
$$d\tau = r(dL \sin \phi + dD \cos \phi)$$

The lift and drag forces are proportional to lift and drag coeffcients with the product of relative dynamic pressure and the local chord length as the proportionality constant, namely

$$dL = \frac{1}{2}\rho_0 V_R^2 \cdot c \cdot c_\ell$$
$$dD = \frac{1}{2}\rho_0 V_R^2 \cdot c \cdot c_d$$

The sectional propeller efficiency may be defined as:

$$d\eta_{\text{prop}} = \frac{V_0 dF}{\omega d\tau}$$

Blade Selection:

Propeller manufacturers offer propellers covering a range of diameters Pitch Values, and solidities. The choice of these parameters can depend on considerations other than the aerodynamics.

Aerodynamically propeller should have a higher efficiency and sufficient thrust for cruise and a high static thrust &r take-off

These two requirements are easier to satisfy with an automatically variable pitch (constant speed) propeller. A fixed pitch propeller is usually a compromise between these two operating regimes.

Given the results of a series of propeller tests, one can utilize these data to select the best propeller diameter and blade angle combination. One approach that is sometimes used is based on a coefficient Cs the speed power coefficient, defined by

$$C_s = (\rho \cdot V^5 / P \cdot n^2)^{1/5}.$$

Recent propeller designs are using highly swept blades, which are reminiscent of swept wings. But in propellers the use of sweep is for different purpose — it is more to control the loss of energy in secondary flow (radial and other non-axial flows). These propellers have started using transonic blade elements to allow the tips to go supersonic and thus permit use of designs for high subsonic aircraft propulsion. Both the aerodynamic design and the mechanical design of these Propellers are posing real challenges to the designers. These propellers are directly coupled to the low pressure turbines, with a possibility of direct drive. Additional problems that come in the way are the noise problems