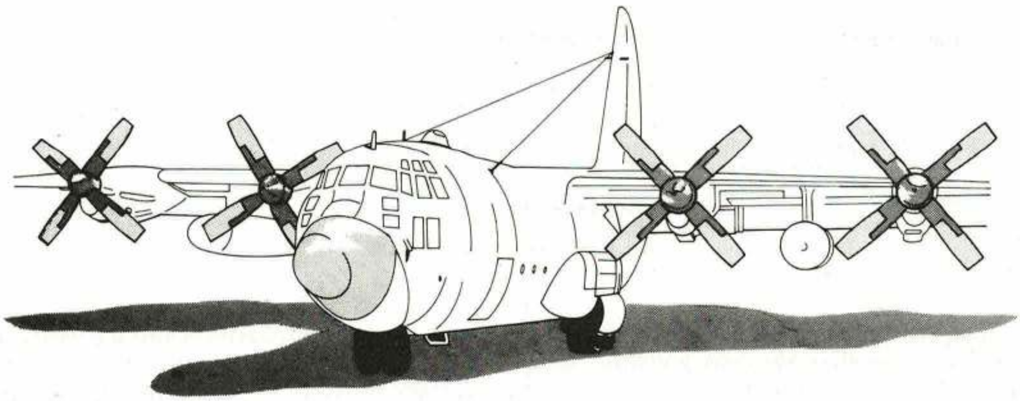
CHAPTER 1

THE AIRCRAFT PROPELLER



Introduction

1. The function of the aircraft propeller is to convert engine torque into thrust (the propulsive force) to enable an aircraft to fly under its own power. The propeller consists of a hub, situated at the centre of a number of radial components, called blades. For many years, the propeller provided the thrust required by all types of aircraft, but it has progressively given way to the gas turbine engine as a means of producing thrust. Today, the propeller is mainly used to provide the motive power needed by many light single and twin engined aircraft, although there are still some large propeller-driven transport aircraft in use; these are usually powered by propeller turbine engines. In the future however, due to the high cost of aviation fuel, the propeller is likely to assume a greater role in the Royal Air Force than it has done for many years. Propellers, driven by gas turbine engines, are likely to be used to provide the motive power needed by such aircraft as those used for pilot training, and for maritime reconnaissance; others may follow.

Propeller Terminology

2. Propeller theory is a relatively complex subject, and hence a considerable number of terms and definitions are used in its explanation. To aid the student in his understanding of propeller theory, a comprehensive list of terms and definitions have been compiled, and included in Annex 'A' to this Chapter.

THE BASIC AERODYNAMIC PRINCIPLES OF A PROPELLER

Lift and Thrust

3. To enable the student to understand how the propeller generates the thrust required to propel an aircraft through the air, the basic aerodynamic principles used in its design must be clearly understood. In many ways, the propeller functions in a similar manner to an aircraft aerofoil surface, which will be explained in the following paragraphs.

4. The propeller blade is a streamlined shape (Fig 5.1.1), which is similar in design to the aerofoil shape of an aircraft wing. When an aerofoil surface is moved through the air, it generates a force called 'lift'. The lift force acts upon the aerofoil in an upwards direction at approximately right angles to the oncoming airstream, and supports the aircraft in the air. A propeller blade generates a similar force as it is rotated through the air, but in this instance the force is known as 'thrust'. It is the thrust produced by the propeller, which causes the aircraft to move forwards through the air.

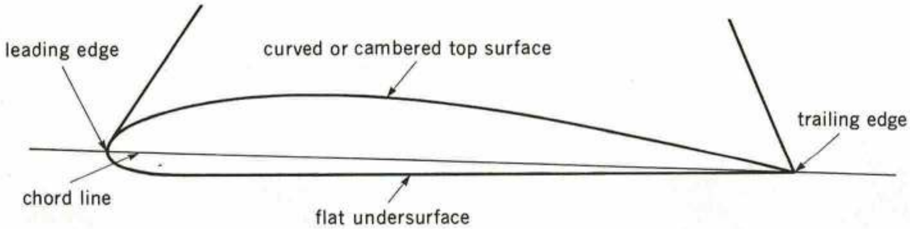


Fig 5.1.1 The propeller blade

5. **The venturi principle.** A useful way of understanding how an aerofoil surface works is to consider the airflow through a venturi tube — a circular tube gradually waisted towards its centre (Fig 5.1.2). If a steady flow of air at a constant pressure is passed through a venturi tube, the velocity of the airstream will increase steadily as the diameter of the tube decreases,

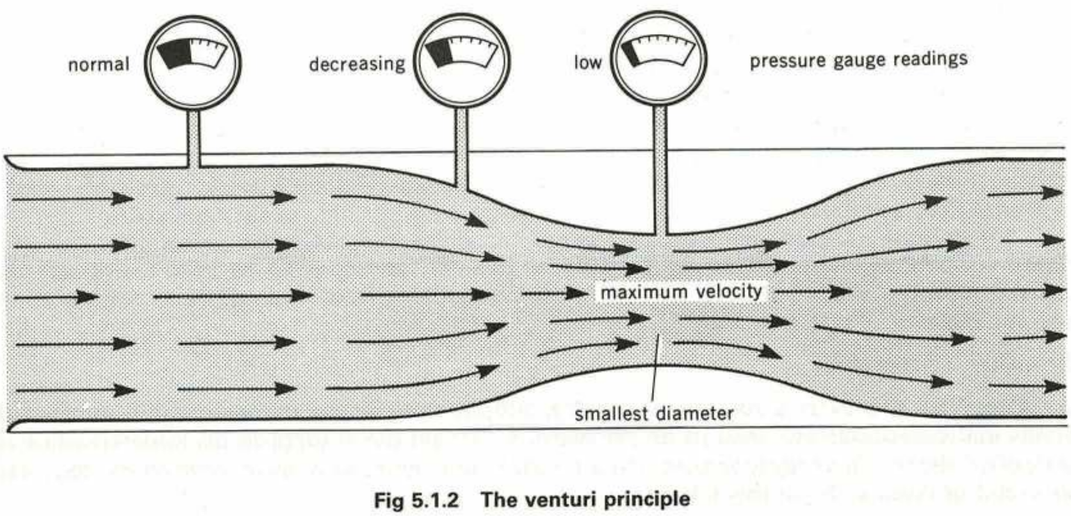


Fig 5.1.2 The venturi principle

and will reach a maximum velocity at the smallest diameter of the venturi. The rate of flow of the air will start to decrease as it passes the smallest diameter of the venturi, and will continue to decrease as the diameter of the tube increases, until the diameter of the tube and the rate of flow of the air return to their original values. If pressure gauges are now fitted within the waisted part of the venturi, it will be seen that the pressure of the airflow decreases as the diameter of the tube decreases. Pressure will progressively return to its original value at the point where the tube diameter has increased to its original size. Hence, it can be seen that if a flow of air is passed through a venturi tube, the velocity of the airstream will increase, and its pressure will decrease as the diameter of the tube decreases. Conversely, when the diameter of the tube increases, the velocity of the air will decrease, and the pressure will increase.

6. **How the propeller blade works.** It has been explained in the previous paragraph how it is possible to change the velocity and pressure of an airstream as it passes through a venturi. If the propeller blade is now considered as an aerofoil shape, the venturi principle may be used to show how the pressure of the airstream changes as it passes over the aerofoil surfaces. In Fig 5.1.3, the airstream is illustrated by what are known as streamlines; these show the flow of air around an aerofoil surface when the chord line of the surface is parallel to the oncoming airstream. The illustration also shows that as the airstream passes over the aerofoil surfaces, there is an increase in velocity and a decrease in pressure over the cambered upper surface of the aerofoil, whilst the velocity falls and the pressure increases over the lower surface.

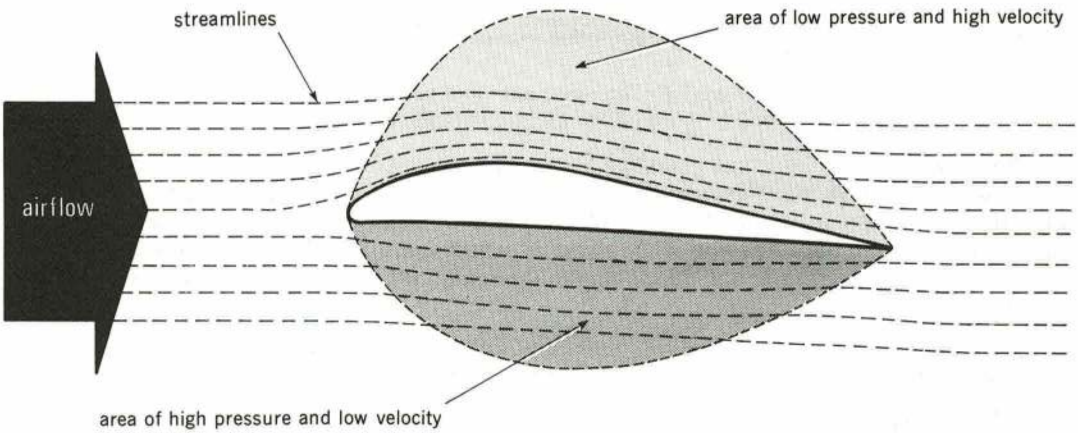


Fig 5.1.3 Airflow around an aerofoil surface

7. **Helix angle.** The theory of the aircraft propeller is more complicated than that of the aircraft wing. This is because the propeller follows a helical path when it is rotating, and each section of the blade travels along a different helix. The actual path followed by a section of a propeller blade is directly opposite to the relative airflow. The helix angle (angle of advance) is measured between the relative airflow and the plane of rotation (Fig 5.1.4). Each section of the blade is set at a different helix angle, because the sections nearest to the blade tip describe a larger diameter helix than sections close to the blade root. The sections near to the tip travel at a higher velocity than those close to the root, and hence have a smaller blade angle.

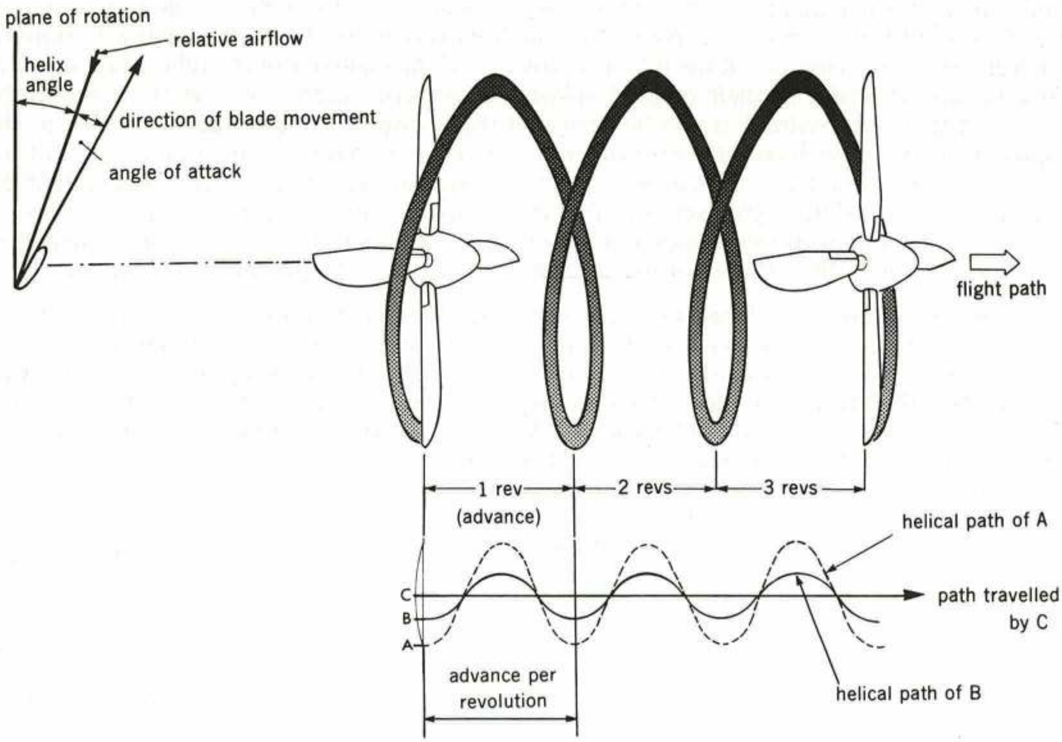


Fig 5.1.4 The spiral path and helix angle

8. **Blade angle.** To ensure that a propeller operates efficiently, each section of the blade is set at an angle known as the 'blade angle'. This angle is greater than the helix angle, and is the angle formed between the chord line and the plane of rotation of the propeller. The blade angle consists of the helix angle and the angle of attack (para 10). The graph illustrated by Fig 5.1.5 shows the variation in the blade angle at various points along the blade of a modern propeller.

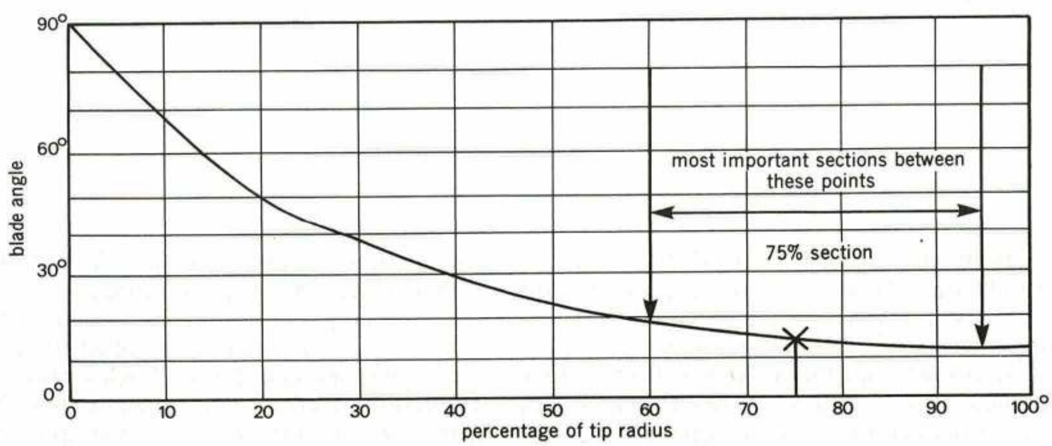


Fig 5.1.5 Variations in blade angle

9. An easy way to understand how the blade angle is defined is shown by Fig 5.1.6. If a propeller assembly is laid on a flat horizontal surface, and a section of one of the blades is viewed from the direction of the tip, the section will appear to be inclined to the horizontal. The blade angle is the sum of the helix angle ϕ and the angle of attack α. The propeller blade is made up of a number of sections, each of which has a different blade angle, and hence the inclination of each section will be different to the section adjacent to it.

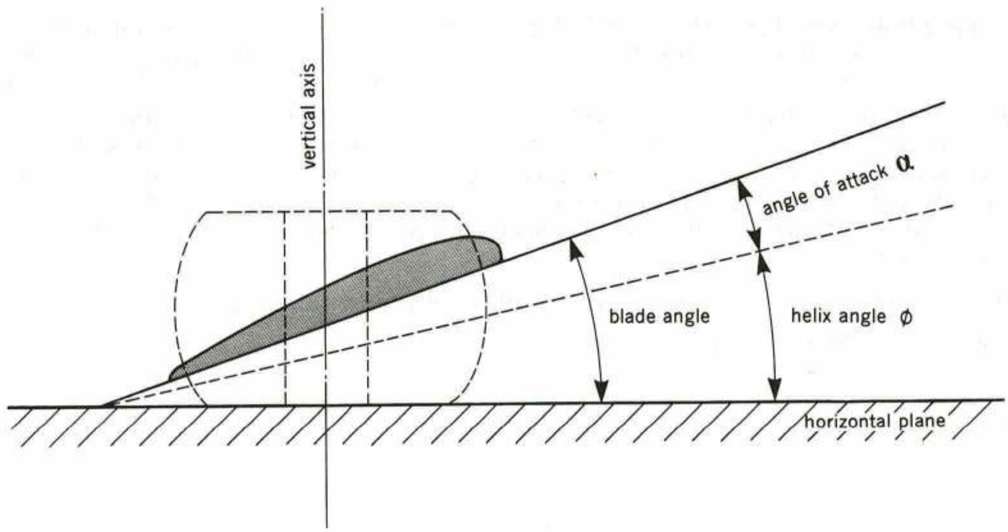


Fig 5.1.6 The blade angle

10. **Angle of attack.** It has previously been stated that if an airstream is passed over the aerofoil surface of a propeller blade, when the chord line of the blade is parallel to the oncoming airstream, the blade will produce thrust. Whilst this is true, the surface will not produce sufficient thrust, if it is held at this angle, to propel an aircraft through the air. The method used to obtain an increase in thrust, is to incline the chord line of the propeller blade to a positive angle to the oncoming airstream. The angle at which the airstream strikes the aerofoil is known as the angle of attack (Fig 5.1.7), and the most efficient results are obtained when the angle is set at approximately 4°. Larger angles of attack may be used, but these are less efficient, because the airflow over the forward face of the blade becomes progressively more turbulent as the angle of attack is increased. When the angle of attack has been increased to approximately 14° – 16°, the airstream flowing over the blade becomes totally turbulent, and all thrust is lost.

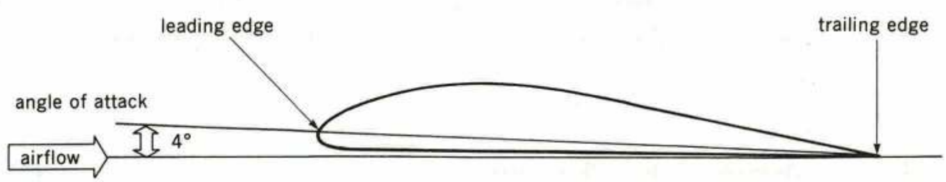


Fig 5.1.7 Angle of attack

11. Each propeller blade is set to a pre-determined blade angle when it is manufactured. However, the blade angle of variable pitch propeller blades may be adjusted, within certain limits, when they are assembled into the propeller hub. It may be necessary to check the basic angle (blade angle) of the propeller blade during the life of the propeller assembly. In such cases, special equipment is usually required to perform this task, and the angle is checked at a specific place on the blade, known either as the 'master station', or alternatively, the 'blade datum'.

12. **The production of propeller thrust.** A propeller is constructed from a number of blades, all of which have aerofoil shapes. Each blade generates thrust as it turns and moves through the air. The forward facing blade surface is, in fact, the upper surface of the previously described aerofoil shape. Hence, the pressure of the air is reduced in front of the blades, which tends to draw more air towards the propeller as it rotates. The rotation of the propeller throws the air rearwards, and forms a moving column of air which passes through the propeller (Fig 5.1.8). The amount of useful thrust produced by a propeller depends upon the volume of air that it can move in a given time, and the change in velocity that the propeller can give to the moving mass of air.

In basic terms, the thrust generated by a propeller can be calculated as follows:

Force = Mass × Acceleration

or

Thrust = Mass airflow through propeller × increase in velocity of the moving airstream.

$= M(V_1 - V_2)$

where M = Mass airflow

V_1 = Velocity of the moving airstream.

V_2 = True airspeed of the aircraft.

The total amount of thrust produced by a propeller assembly is the sum of the thrust produced by each blade.

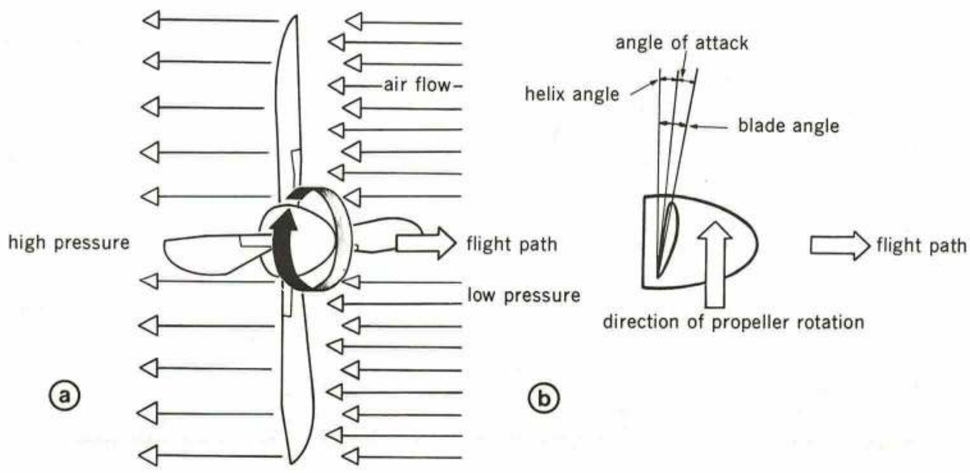


Fig 5.1.8 Production of propeller thrust

13. **Factors affecting propeller thrust.** The amount of useful thrust produced by each propeller blade depends upon various factors, some of which are as follows:

- The shape of the aerofoil and the smoothness of its surface.
- The speed of the airflow over the aerofoil.
- The angle of attack of the aerofoil.
- The density of the air.

14. **Momentum of the airflow.** If we now consider the mass airflow moved by the propeller to generate thrust, it can be proved that when the air is moved at a velocity 'v', it will be given momentum. It has already been established that thrust is the product of the mass of the moving airflow and the increase in its velocity. But the amount of thrust generated by a propeller is also equal to the rate at which momentum is given to the air.

Thus: $\text{Thrust} = M(V_1 - V_2)$ – as shown in para 12;

and momentum $= Mv = \text{Thrust}$;

where M = Mass of air in kg;

v = Change in velocity of the air.

When a mass of air is given momentum, it is also given energy, which varies according to the mass of the air moved, and the velocity of the airstream. The energy given to the airstream depends mainly upon the change in its velocity. Much of the energy given to the air is absorbed in the form of heat, and is then dissipated into the surrounding air and totally wasted. The energy absorbed by an airstream may be shown in a simple way by calculating the work done to move different masses of air by various velocities. The work done in moving the air is known as its kinetic energy, and is derived from the formula; $KE = \frac{1}{2}mv^2$, in units of joules. Thus, if a 5 kg mass of air is moved at a velocity of 10 m/s, the work done in moving the air is as follows:

$$KE = \tfrac{1}{2} mv^2 \text{ joules}$$
$$= \tfrac{1}{2} \times 5 \times (10)^2$$
$$= 250 \text{ joules.}$$

Alternatively, if a 10 kg mass of air is moved at a velocity of 5 m/s, the work done is:

$$KE = \tfrac{1}{2} mv^2 \text{ joules}$$
$$= \tfrac{1}{2} \times 10 \times (5)^2$$
$$= 125 \text{ joules.}$$

However, the momentum given to the air in both examples is the same, and each produces an identical amount of thrust. These examples show that the higher the velocity of the air, the greater will be the amount of energy absorbed into the airstream. The propeller would appear to offer the most efficient method of producing thrust in this respect, in that it moves a large volume of air with a relatively small change in velocity. The gas turbine engine moves a smaller volume of air, but generates a larger change in velocity, whilst the rocket engine moves an even smaller volume of air at an even higher velocity.

15. **Propeller efficiency.** In the previous paragraph, the propeller has been shown to be an efficient way of producing thrust. However, there are other factors which must be considered when propulsive efficiency is being assessed. Two of the most important factors to be considered when assessing efficiency are the velocity at which an aircraft is required to fly, and

the proportion of engine torque that is absorbed by the propeller. Maximum propeller efficiency is achieved when the engine torque has been fully absorbed by the propeller. If reference is now made to Fig 5.1.9, it will be seen that the propeller provides the most efficient method of propulsion at lower speeds, whilst the gas turbine engine and the rocket engine are more efficient at considerably higher speeds. There are other factors affecting efficiency which will not be considered at this stage. It must be remembered however, that propulsive efficiency is just one factor which is taken into account when the method of propulsion of an aircraft is chosen.

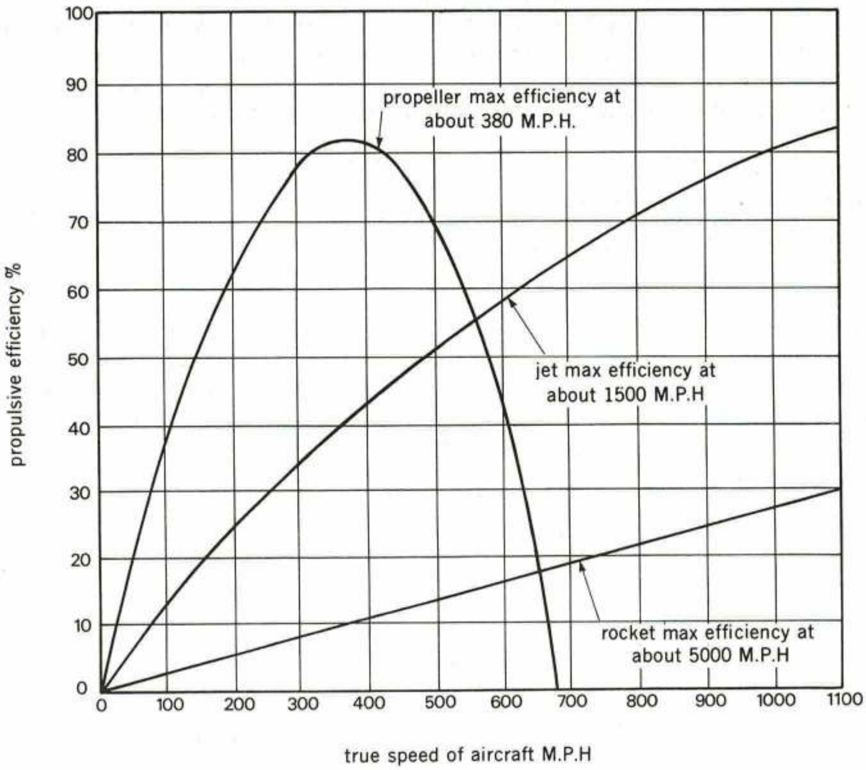


Fig 5.1.9 Propeller efficiency

The Propeller Blade

16. **Blade twist.** It has already been established that useful thrust is produced when a propeller blade is inclined at a small angle to the oncoming airstream (angle of attack). Effectively, this means that when the aircraft is in flight, the propeller blades describe a spiral path along the longitudinal axis of the aircraft (Fig 5.1.4). The distance moved forward along the longitudinal axis, or the flight path, is the same for all sections of the blade. Because of the spiral path followed by the blade, the sections nearest to the tip travel greater distances through the air, and hence move at a higher velocity than the sections at, or near to the blade root. Thus, in order to ensure that the propeller blade generates as even an amount of thrust as possible along its entire length, the blade angle is varied from a large (coarse) angle at the root of the blade, to a small (fine) angle at its tip. The variation in the angle of the blade produces a helical shape which is known as the 'blade twist'.

17. **Relative airflow.** In earlier paragraphs of this Chapter it has been stated that a propeller blade has an aerofoil cross section, and that a flow of air passes over its surface in a similar way to an aircraft wing, when the propeller is turned by the engine. However, because the propeller is rotating, and moving forward along the aircraft flight path at the same time, the direction of the airflow over the propeller blade will be different to that of the aircraft wing. The actual direction of the airflow will be the resultant of the forward and the rotational velocities as shown by Fig 5.1.10. The resultant, known as the relative airflow, varies for each section of the blade.

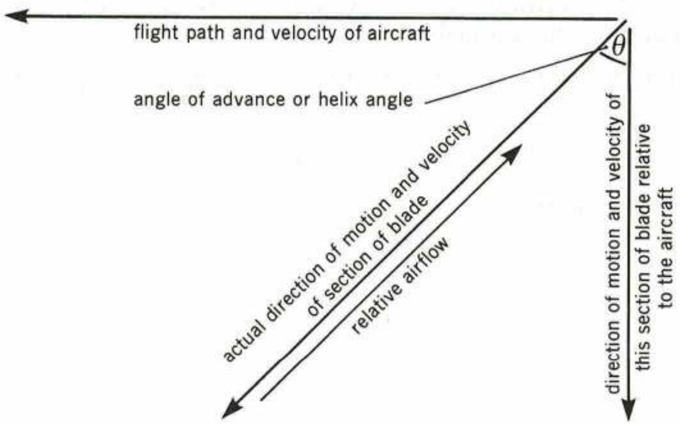


Fig 5.1.10 Relative airflow

18. **Propeller forces.** The blade rotation generates 'lift' and 'drag' in a similar way to an aircraft wing. However, these forces are of little practical use when assessing the performance of a propeller (Fig 5.1.11a). With the propeller, the most important forces are:

- Those acting along the longitudinal axis of the aircraft. These forces are known as the 'thrust' of the propeller.
- Those acting at right angles to the propeller rotation. These forces are known as the propeller 'torque'. (A turning moment generated when a propeller rotates).

Thus, the total reaction may be resolved into thrust and torque forces (Fig 5.1.11b).

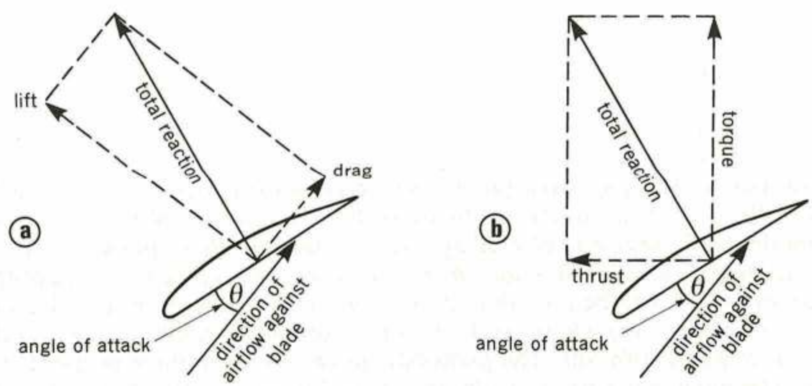


Fig 5.1.11 Propeller forces

Propeller Pitch

19. If a nut is turned on a bolt, it will move along the bolt, and the distance that the nut moves in one revolution is called the 'pitch'. This basic principle can also be applied to the propeller. If we take a section of a propeller blade, r metres from its axis, and rotate the propeller through one revolution, without moving forward, it will travel a distance which is equal to the circumference of a circle, ie $2\pi r$. Let the section of the propeller blade now move forward a distance 'p' metres in one revolution of the propeller. The spiral distance moved forward by the section under consideration, will be equal to the hypotenuse of a right-angled triangle with a base of '$2\pi r$' metres, and a height of 'p' metres (Fig 5.1.12). The height of the triangle is equal to the propeller pitch — the distance the aircraft has moved along its flight path in one revolution of the propeller.

In the illustration, the angle θ represents the blade angle of the propeller section. Thus

$$\text{Tan}\ \theta = \frac{p}{2\pi r}$$

$$\text{and}\ p = 2\pi r\ \text{Tan}\ \theta$$

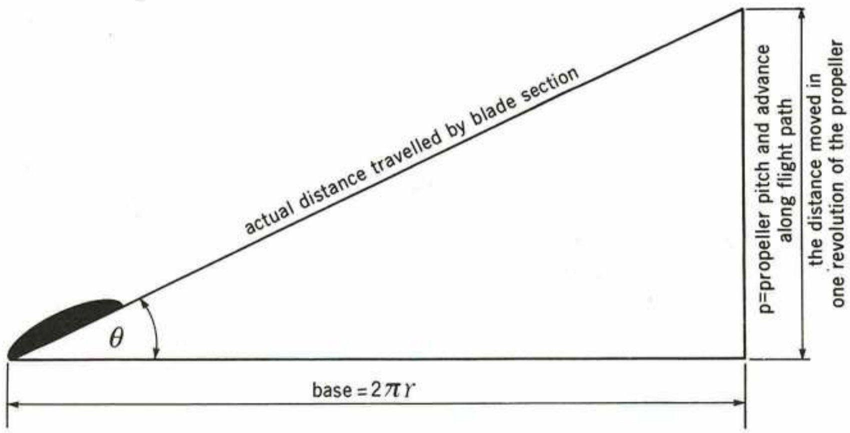


Fig 5.1.12 Propeller pitch

20. **Geometric pitch.** Consider a section of a propeller blade which is 'r' metres from the axis of the propeller, and has a blade angle of $\theta°$. Under certain conditions of flight, the angle of attack of the blade will be zero. Hence, the blade section will rotate in a path which is parallel to its chord line, and will move forward a finite distance 'p'. This is known as the geometric pitch of the propeller. The geometric pitch can be further explained if reference is made to Fig 5.1.13. In this illustration, a number of blade sections are shown at various distances ($2\pi r_1$, $2\pi r_2$ etc) from the blade axis, and plotted against a vertical height of pitch 'p'. The lines drawn from each section are elevated at angles θ_1 θ_2 etc, where θ represents the appropriate blade angle for that section. It will be seen that all the lines intersect at point 'p'. This shows that as the radius 'r' increases, the blade angle becomes proportionately smaller, and hence the geometric pitch remains constant. The geometric pitch of a fixed pitch propeller is set during manufacture. The pitch may vary from about 1 metre for a slow type of aircraft to 5 metres for a racing aircraft.

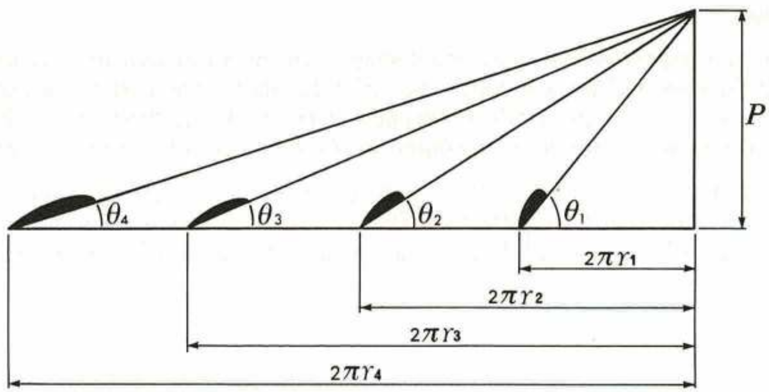


Fig 5.1.13 Geometric pitch

Main Thrust Area of a Propeller Blade

21. Despite careful design and manufacture, the propeller blade cannot be made to be equally efficient throughout its length. There are unavoidable aerodynamic losses near the root end and also at the blade tip. These cause variations in the thrust and torque which is felt along the length of the blade. Near the root end, the blade must be thick to provide the necessary strength, which means that the sections in this part of the blade are of poor aerodynamic shape. The airflow over the sections of the blade near the root is affected by the propeller hub and by the bulk of the engine, particularly for pusher type propellers. These sections of the blade are the least efficient, and contribute very little to the thrust. Additionally, the tip of the blade loses some of its efficiency because of the tip vortices and the associated vortex drag that it generates. At high rotational speeds even more losses are incurred due to the effects of compressibility. If reference is now made to Fig 5.1.14, it will be seen that most of the thrust is generated from a relatively small area of the blade; and the areas which incur significant losses, considerably reduce the overall efficiency of the blade.

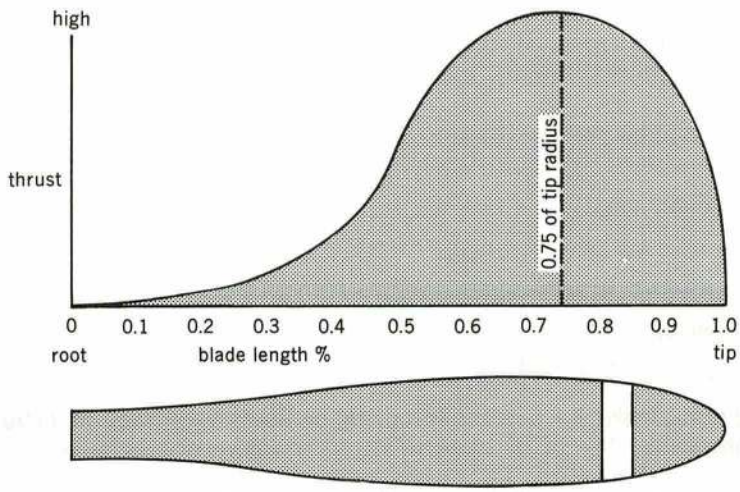


Fig 5.1.14 Propeller blade efficiency

Blade Stations

22. To assist in the production of accurate shapes, propeller blades are divided into sections, which start at the root and work towards the tip of the blade. The end of each section is said to be a 'blade station' where the blade is checked to prove the accuracy of its shape and angle. Between each station, the blade is machined to provide a smooth even change in its profile.

23. **Master station.** The 'master station' is the position on a propeller blade where the blade angle is measured for reference purposes. It may be located by measurement from the hub, and is usually identified by an indelible mark which is drawn chord-wise across the thrust face of the blade.

Propeller Size

24. The size of a propeller depends largely upon the amount of thrust needed to give an acceptable performance to a particular aircraft/engine combination. The greater the engine power, the larger is the propeller needed to convert the power into thrust. However, the blade tip speed or the tip clearance above the ground will eventually limit the practical diameter of the propeller. If the thrust required for a particular engine/airframe combination is greater than the amount of thrust that a two bladed propeller can produce, then a propeller with more blades must be used.

25. Propellers have been produced with a single counter-balanced blade, but in general, two, three or four-bladed assemblies are most commonly used. However, it must be understood that larger diameters and more blades are not the only means of producing more propeller thrust. The use of blades which have a longer chord, or those which alter the section of the blade can also change the amount of thrust obtained from a propeller of a given diameter.

26. Since the forward movement of an aircraft increases the speed of the airflow over the propeller blade, the propeller will operate most efficently at low rotational speeds. The internal combustion engine gives its maximum power at comparatively high rotational speeds; hence, there is a considerable difference between the speed of operation of the engine and the speed of rotation of the propeller. Small diameter propellers can revolve at comparatively high speeds, and still give satisfactory results when used with small piston engines. However, when it is necessary to transmit the power produced by more powerful engines, larger propellers must be used. The power produced by a more powerful engine is transmitted to the propeller through a reduction gear. The use of a reduction gear enables both the engine and the propeller to rotate at their most efficient speed (ie the engine turning at a high rotational speed and the propeller at a low rotational speed).

27. **Absorbing the engine power.** The amount of engine power that is able to be absorbed by a propeller can be increased by employing some or all of the following methods:

- Increasing the blade angle.
- Fitting a blade with an increased chord.
- Increasing the number of blades.
- Fitting longer blades.
- Increasing the camber of the blade.

In the following paragraphs, each of the foregoing methods is assessed, in turn, as a means of absorbing engine power.

28. **Increasing the blade angle.** It has already been established that a specific blade angle provides the optimum angle of attack for maximum propeller efficiency. To increase the blade

angle beyond this point will not bring about any increase in propeller efficiency. Thus, to increase the blade angle beyond the optimum setting is a waste of useful extra engine power.

29. **Fitting a blade with an increased chord or increasing the number of blades.** These are both acceptable ways of absorbing additional engine power and producing more thrust. The two methods may be considered together as they both provide a method of increasing what is referred to as the 'solidity' of a propeller. The solidity of a propeller is the ratio between that part of a propeller disc which, when viewed from the front, is filled by the blades, and the remainder of the disc which is filled by air (Fig 5.1.15). Solidity is measured by adding together the blade chords at a particular point on the blades (such as the master stations) and dividing the sum by the circumference of the propeller disc at that radius. The greater the solidity, the greater is the amount of engine power that can be absorbed by a propeller and converted into propulsive thrust. Thus, it can be seen that the solidity of a propeller can be increased by using more propeller blades or conversely, by using a smaller number of blades which have an increased blade chord (propeller width). The addition of more blades is the most efficient way of increasing the thrust obtained from a fixed diameter propeller. However, because of the complexity of the hub, the number of blades is usually limited to four. A simple way to increase the solidity of a propeller blade is to increase the chord length. The wider type of blade is usually rounded at its tip, to reduce the overall diameter of the propeller. Such blades are called 'paddle blades', because they appear to be exceptionally wide when compared to their length. However, there is a limit to the amount that the chord can be increased; an excessive chord length will decrease the efficiency of the blade and increase the centrifugal turning moment, thus imposing a greater strain upon the pitch-change mechanism.

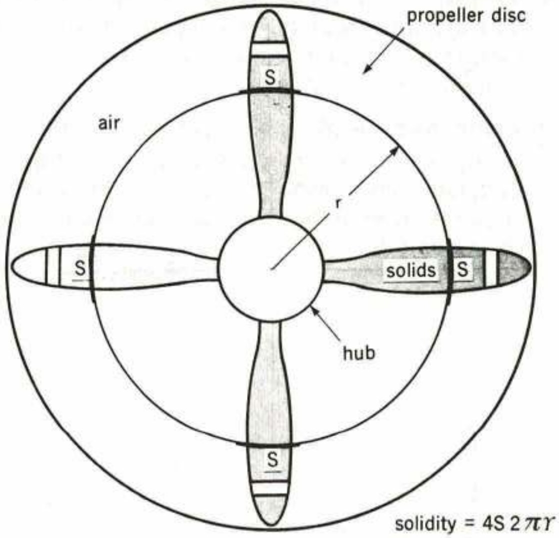


Fig 5.1.15 Propeller solidity

30. **Fitting longer blades.** The diameter of a propeller is often governed by the blade tip clearances from the ground, and the speed that they move through the air. The length of a propeller blade is also limited by the size of the aircraft and the position of the engines in the airframe. Hence, the use of longer propeller blades is unlikely to provide a satisfactory solution when it is necessary to absorb extra engine power.

31. **Increasing the blade camber.** When the camber of a propeller blade is increased, the thickness is also increased, and this, in turn, enables a propeller to absorb more engine power. However, an increase in the camber of the blade will bring about a reduction in its efficiency, and hence is not a useful means of absorbing increased engine power. In fact, designers of modern propellers tend to employ thin aerofoil sections to avoid a loss in efficiency at high rotational speeds.

Propeller Forces and Balance

32. **Forces acting upon a propeller.** When an aircraft is flying, the propeller is subjected to various forces. These forces can cause severe vibration in the aircraft unless the propeller is properly balanced. The main forces are:

- **Centrifugal force.** This force is caused by the rotating mass of the propeller blades, it tends to pull the blades out of the hub (ie the force acts along the blade axis). The mass of the blade is positioned about the blade axis in such a way that a second force is set up, called the centrifugal twisting moment (CTM). Referring to Fig 5.1.16, it will be seen that this force acts radially around the blade and tends to reduce the blade angle. The longer the chord of the propeller blade, the greater is the effect of the CTM.
- **Thrust.** The propeller blade produces a considerable amount of thrust when it is rotated, and this produces a force acting in the direction of flight, tending to bend the blades forward. To enable a propeller assembly to run smoothly, each blade must produce the same amount of thrust.
- **Aerodynamic loads.** The propeller's aerodynamic loads are forces which are generated by the blade as it moves through the air. In addition to the thrust and CTM loads, the propeller generates an opposing force to the CTM, which tends to increase the blade angle. Imperfections in the shape and the angle of the blades can upset the aerodynamic balance of the assembly.

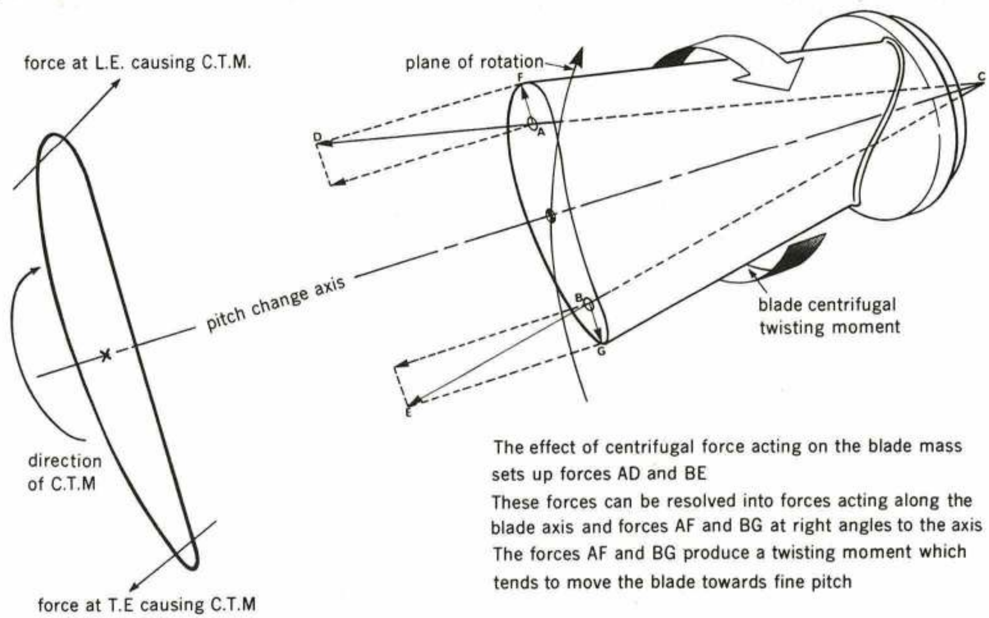


Fig 5.1.16 Centrifugal twisting moment

33. **Balance.** Unless a propeller assembly is properly balanced, the assembly will be subjected to severe vibration, which will then be transmitted through the entire airframe structure. To eliminate propeller vibration, each propeller assembly is subjected to a comprehensive balancing process before it can be fitted to the propeller shaft of an aircraft engine. During balancing, the weight of each blade is adjusted so that there is an even and balanced distribution of the blade mass about the hub. If the profile of each blade is not identical, some minute variation of the blade angle may be used to provide an aerodynamic correction. All such details are recorded on the propeller blade log card for future reference, and in some instances, changes in the blade angles are recorded on the blades themselves. Details of propeller balancing will be included in Chapter 5 of this Section.

Propeller Installations

34. It has been stated previously that a propeller assembly consists of a number of blades fitted into a hub (Fig 5.1.17). The purpose of the assembly, which is fitted to the engine propeller shaft, is to convert engine power into a pulling or pushing force acting along the longitudinal axis of the aircraft. This force is the previously defined thrust generated by the propeller as it is turned by the engine.

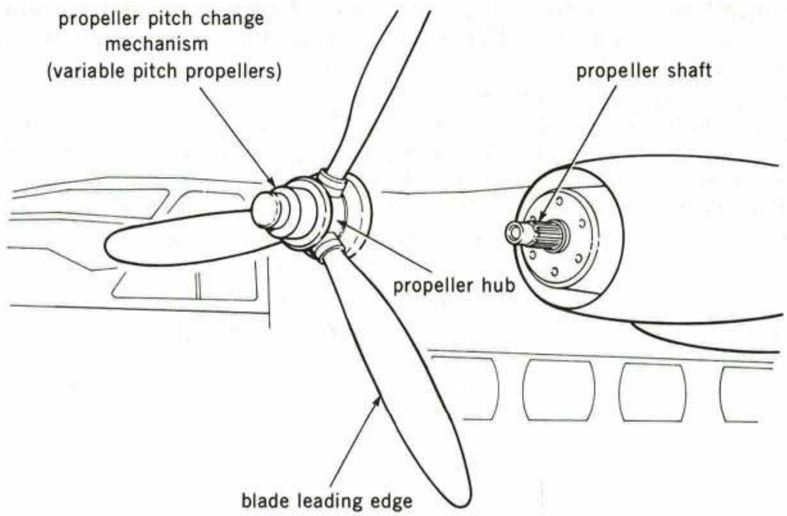


Fig 5.1.17 Propeller and shaft

35. There are different ways in which a propeller may be mounted onto an aircraft, depending upon its design (Fig 5.1.18). A propeller may be mounted in front of an engine, so that the propeller shaft is in tension when the propeller produces thrust. This type of propeller is known as a 'tractor' propeller. On some aircraft, the engine and propeller are mounted at the rear of the aircraft, and push it through the air; these are known as 'pusher' propellers. Aircraft engines may be designed to rotate in either a clockwise direction, or a counter-clockwise direction. Dependent upon the design of the aircraft, and its engine(s), propellers may be designed to fulfil any of the following functions:

- Right-hand tractor
- Left-hand tractor
- Right-hand pusher
- Left-hand pusher

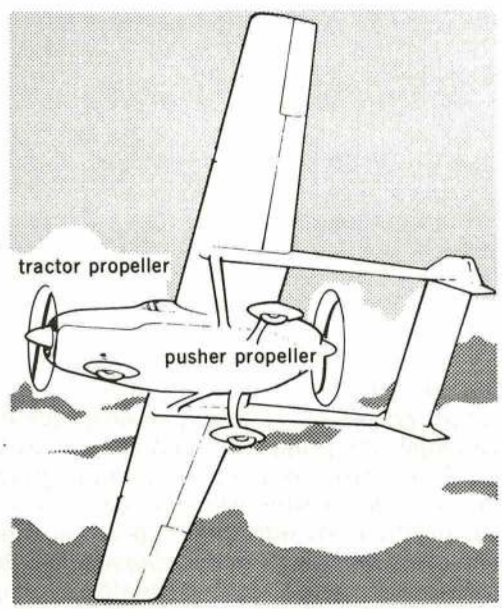


Fig 5.1.18 Tractor and pusher propellers

Propeller Types

36. Propeller blades are manufactured from specially selected wood, or non-ferrous metal, and are made into one of two basic types:

- Fixed pitch propellers.
- Variable pitch propellers.

37. **Fixed pitch propellers.** Modern fixed pitch propellers are two bladed, and are usually fitted to light aircraft that are powered by small piston engines. The blades are manufactured with a fixed blade angle that has been selected for a particular airframe/engine combination, and hence the angle chosen is a compromise between the angles required for the take-off, flight, and landing phases of operation. The angle of attack for a fixed pitch propeller varies with changes in the engine's rotational speed and the aircraft's forward speed, which limits the efficient performance range of the propeller. When a coarse (large) blade angle is used, the take-off and climb performance of the aircraft will be poor, because the propeller's angle of attack is to large to allow the propeller to perform efficiently at low aircraft speeds. If a fine (small) blade angle is used, the angle of attack of the propeller will suit its efficient operation at low forward speeds. However, since the angle of attack gets smaller as the aircraft speed increases, a negative angle of attack can be produced if the aircraft is put into a dive. Thus, it can be seen that for general use, neither a fine nor a coarse blade angle will suit all aircraft flight conditions, and hence the angle chosen must be a compromise between the fine and coarse angles to provide an acceptable aircraft performance.

38. **Variable pitch propellers.** A variable pitch (VP) propeller assembly can be fitted with two, three or four blades. The blade angle of such propellers can be adjusted whilst the aircraft is in flight. The blades are fitted into a hub, and may be rotated about the axis of the blade to provide a variation in the pitch angles. The range of movement of the blades is controlled by what are known as 'fine' and 'coarse' pitch stops. The pitch stops limit the range of movement of the blade to the design range for a particular aircraft/engine combination. Movement of the blades between the pitch stops is achieved by using a controller, known as the 'constant speed unit' (CSU). The CSU is sensitive to rotational speed, and is connected to a pitch change mechanism.

The introduction of the VP propeller solved the main problem associated with the use of a fixed pitch propeller; that is the maintenance of propeller efficiency throughout the flight envelope of an aircraft. By using a VP propeller, it is possible to adjust the blade angle when an aircraft is in flight. Thus the angle of attack of the propeller blade can be kept at, or near to, the optimum setting for the forward speed of the aircraft, maintaining the propeller at its most efficient operating angle. A fine pitch angle is therefore available to produce an angle of attack that is suitable for take off, acceleration, and climb. There is also a coarse pitch setting available to provide the correct angle of attack for cruising or high speed flight (Fig 5.1.19). Some small VP propellers provide only a two position (fine and coarse) setting; but most VP propellers can be adjusted to any angle within the fine and coarse pitch limit stops. When the pitch setting of a modern variable pitch propeller is automatically adjusted in flight, it is called a 'constant speed' propeller. This type of propeller is controlled by a constant speed unit (CSU), and maintains the propeller speed selected by the pilot irrespective of engine throttle opening or the flight manoeuvres of the aircraft within the constant speed range. VP propellers fitted to the engines of multi-engined aircraft are provided with a means of moving the blades beyond the coarse pitch setting to a position which presents the minimum blade thickness to the oncoming airflow. This propeller setting is known as 'feathering', and is used in cases of engine failure to minimise the drag created by a windmilling propeller. Some large aircraft are fitted with propellers that can be turned beyond the fine pitch setting, to produce a negative angle of attack and generate an aircraft braking effect known as 'reverse thrust'. Such propellers enable aircraft to land on much shorter runways, and minimise the use of wheelbrakes during the landing run.

Propeller Materials

39. **Wooden propellers.** In the early years of aviation most aircraft propellers were manufactured from wood, some of which had steel or alloy hubs. The blade was usually constructed from a number of birch or mahogany planks, glued and pressed together. When the glue was set, the wood was machined to form a streamlined shape, with the required contour. Fixed pitch propellers usually had an integral boss that was fitted to take a metal hub. The hub was then fitted onto the propeller shaft. The propeller was secured onto the hub by long through bolts and disc-like face plates.

40. The blades of wooden propellers were either polished and varnished, or they were covered by a special protective sheath, depending upon the type of wood used in their construction. Whatever the external finish, a non-ferrous metal sheath was fitted to the leading edge of each blade. However, few wooden propeller blades are manufactured today; modern aircraft are fitted with propellers that have an all-metal construction.

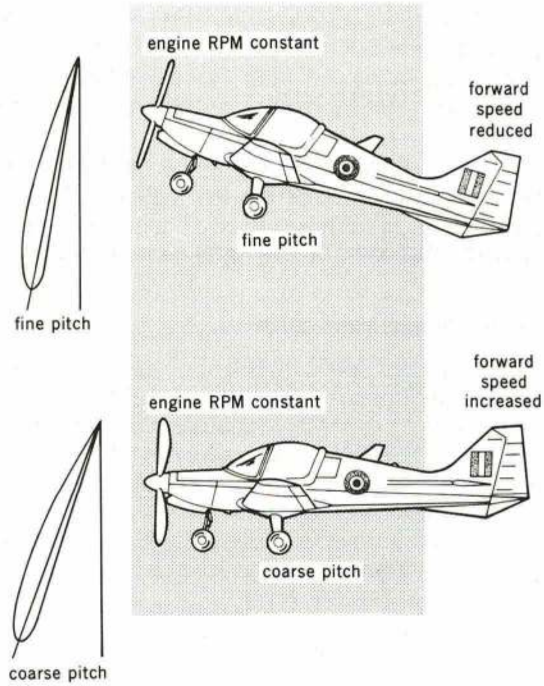


Fig 5.1.19 Variable pitch propellers

41. **Metal propellers.** Metal propeller blades are usually manufactured from duralumin forgings that are machined to shape, anodised and then dyed to provide a corrosion resistant external surface. Fixed pitch metal propellers have an integral boss that is bolted on to a steel hub fitted onto the propeller shaft. VP propeller blades are fitted and screwed to accept the root end fittings necessary to accommodate a pitch change mechanism. The blades are fitted into an alloy steel hub, and held in bearings that allow each blade to turn about its axis. Propeller hubs have a hollow splined core, which fits onto the propeller shaft. When a VP propeller is fitted to an aircraft, provision is made on the front of the propeller hub for a pitch change mechanism to be fitted to the hub.

Propeller Identification

42. All items of equipment used by the Royal Air Force are identified by a management code and stock number. In addition to the management code and stock number, propellers are allocated a group code or propeller model number by the propeller manufacturer, describing the main identifying features of the propeller. An example of a model number, as allocated to the Hamilton Standard propellers fitted to the Hercules aircraft, is as follows:

Propeller Model Number 54H60-91: where –

5 denotes the evolution from the basic propeller.

4 denotes the number of blades.

H denotes the propeller blade shank size.

60 denotes the SAE standard shaft size.

91 denotes the function and installation characteristics.

43. Each propeller assembly and its associated blades are given a unique serial number at the time of manufacture, providing a positive means of identification throughout their service lives. Log cards are also raised by the propeller manufacturer, which must be maintained throughout the life of the propeller in accordance with normal documentation procedures.

44. All propellers are identified on the hub of the propeller with the group code number and the serial number that has been allocated to the assembly. The markings may be repeated on each blade, in addition to the blade serial number. When a propeller is being replaced on an aircraft, the code of the replacement must match the code of the propeller to be replaced.

Pitch Change Mechanism

45. **Constant speed.** Modern propellers are often referred to as VP constant speed propellers. A constant speed propeller is fitted with a special control mechanism which varies the pitch angle of the propeller to maintain a constant load upon the engine; this enables the engine to rotate at a constant speed. The pitch change mechanism is fitted to the front of the propeller. It is usually operated hydraulically by a high pressure oil supply, which is controlled by an rpm sensitive control called the 'constant speed unit' (CSU). The CSU is connected through mechanical linkage to a lever in the aircraft cockpit, known as the 'pitch control lever'. This enables the aircraft pilot to change the angular setting of the propeller as and when required.

46. Pitch change mechanism designs vary considerably between individual manufacturers, and hence, they will not be described in this Chapter. Information on individual designs will however be given later in the Section. A simple illustration of the pitch change mechanism principle is shown in Fig 5.1.20, to give the reader a basic idea of how the mechanism works.

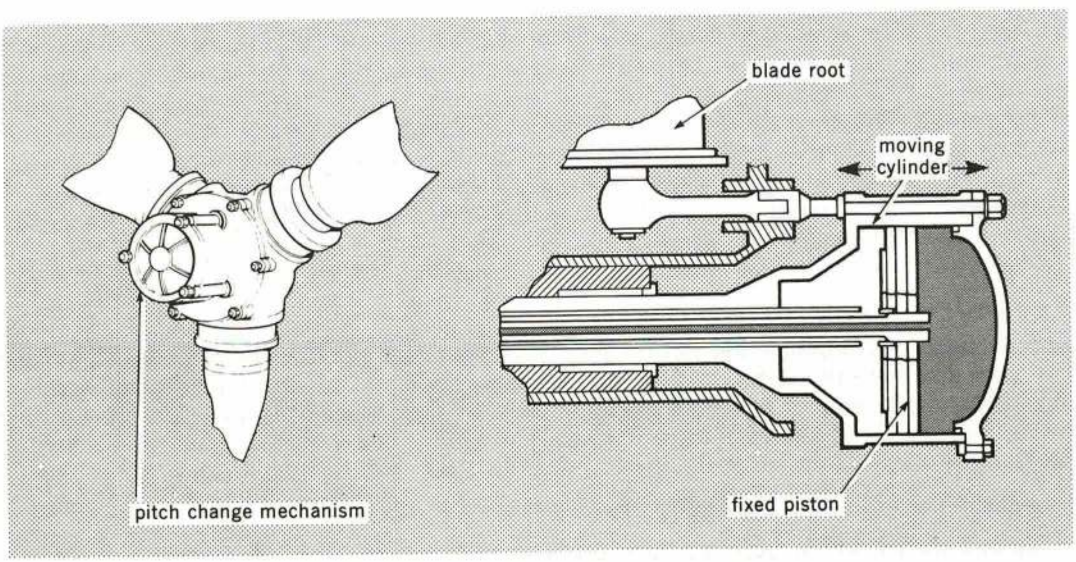


Fig 5.1.20 Pitch change mechanism

Constant Speed Units

47. The CSU, or 'Propeller Governor Unit' as it is sometimes called, is usually mounted on the engine casing. It is driven from the engine gear train, and is usually supplied with pressurized oil from the engine lubrication system (Fig 5.1.21). The basic unit consists of a mechanical flyweight type centrifugal governor unit; it is fitted with a conical spring, and seated onto the base legs of the governor flyweights. Oil is pressurized by a gear type oil pump, and is then delivered through oilways to a piston type control valve. The control valve directs the flow of oil to the pitch change mechanism, which changes the pitch of the propeller as required by the aircraft pilot.

48. The position of the control valve is controlled by the engine rpm and the pressure of the conical spring on the base legs of the flyweights. When the engine speed is below the selected value, the spring pressure is greater than the contrifugal force generated by the flyweights. The spring force will then overcome the centrifugal force, causing the control valve piston to slide in its housing and uncover port C. Pressurized oil will now flow from the oil pump, through control valve ports A and C to the pitch change mechanism, causing the propeller blades to rotate towards the fine pitch setting and allow the engine and propeller speed to increase. An increase in engine speed will in turn rotate the flyweights at a greater speed, generating a greater centrifugal force. An increase in the centrifugal force overcomes the conical spring pressure, and the control valve is returned to the neutral position when the engine speed has increased to the required value. When the engine speed is greater than the selected rpm, the control valve will operate in the reverse sequence, and the pitch change mechanism will rotate the propeller blades towards the coarse pitch setting. This will increase the load on the propeller and reduce the engine rpm to the required value.

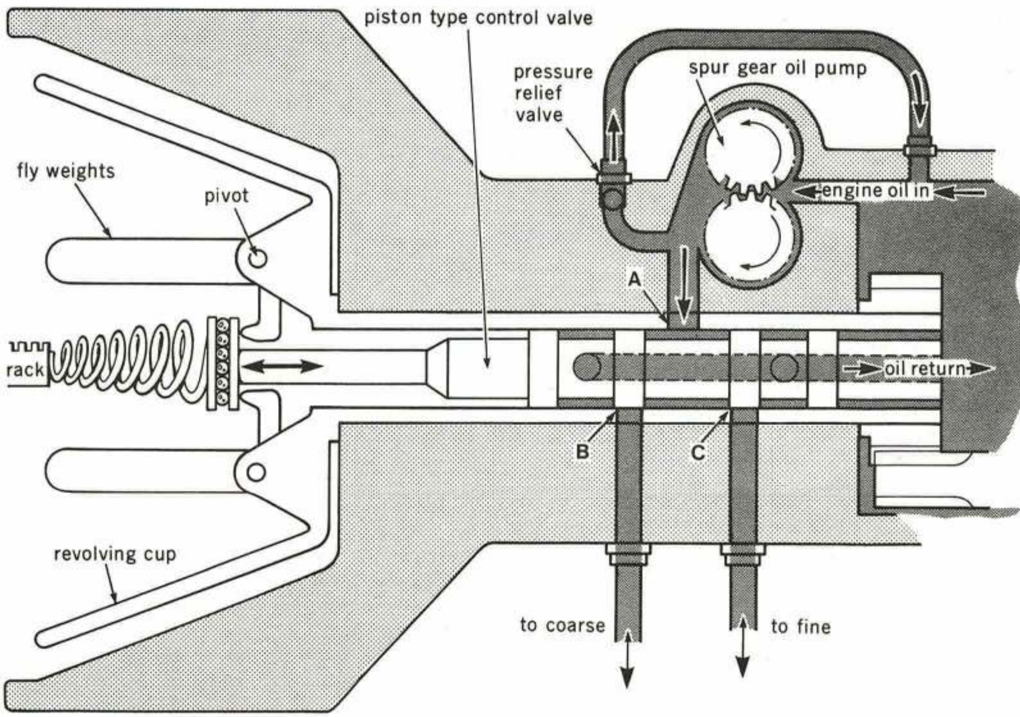


Fig 5.1.21 Constant speed unit

Spinners

49. To reduce propeller drag, and to promote a smooth airflow pattern over the hub of a propeller, the hub and the pitch change mechanism are covered by a special domed shell, called a 'spinner' (Fig 5.1.22). A spinner assembly is usually manufactured in two parts; a backplate is fitted to the rear face of a propeller hub, and the spinner to the forward face. The spinner is usually attached to the backplate by quick release fasteners, and may be removed easily by unlocking the fasteners to gain access to the propeller hub and pitch change mechanism. Blade root fairings are fitted to the back plate to smooth the flow of air around each propeller blade.

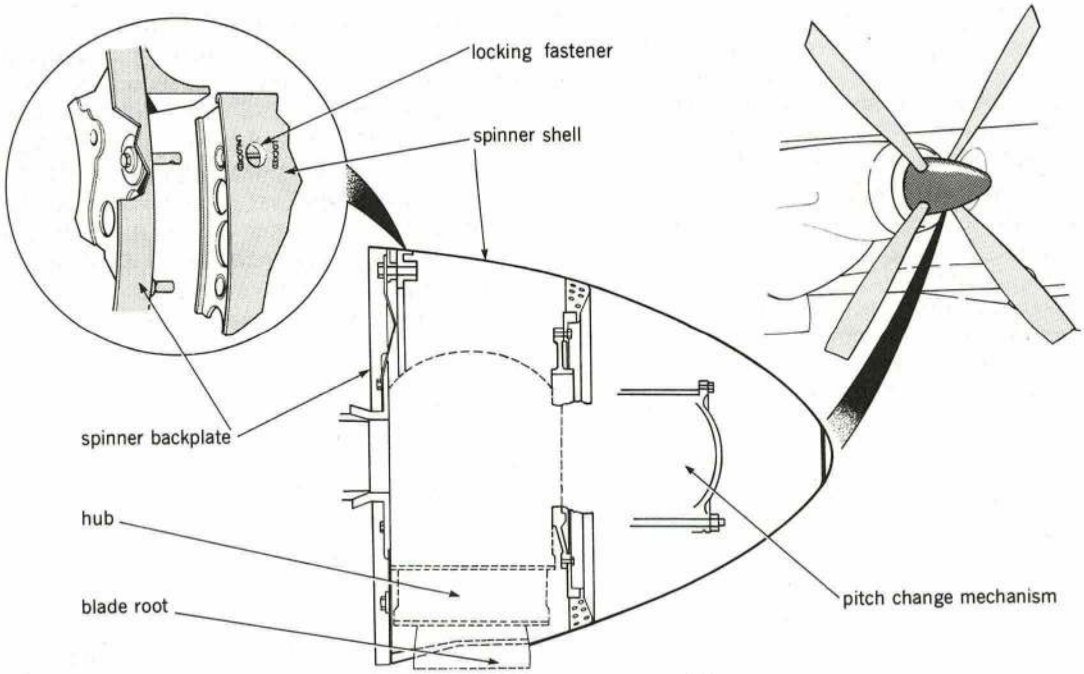


Fig 5.1.22 The spinner assembly

Conclusion

50. This Chapter has explained in a general way, and in relatively simple terms, the basic theory of propeller propulsion. It has also dealt with the different types of propeller, and their associated equipments. The Chapter has been designed to assist the student in gaining an understanding of propeller propulsion before more advanced courses of study are undertaken.

ANNEX A – GLOSSARY OF PROPELLER DEFINITIONS AND TERMS

A glossary of the most commonly used terms associated with aircraft propellers is given below; the list has been designed to assist the student whilst studying propeller theory.

- **Purpose of a propeller.** To convert the engine shaft power into thrust.
- **Thrust.** The aerodynamic force attributed to the propulsion system. It is the component of the total reaction force acting at 90° to the plane of rotation which is generated when a large mass of air is accelerated rearwards by a propeller.
- **Aerofoil.** A body that is so shaped that it produces an aerodynamic reaction (lift) normal to the direction of motion of the body. The shape of the propeller blade is an aerofoil section, which enables air to pass smoothly around the blade whilst producing thrust.
- **Chord line.** The chord line of an aerofoil section is a line joining the centre of curvature of the leading edge to the centre of curvature of the trailing edge of the aerofoil.
- **Relative airflow.** When an aerofoil section is moving forwards through the air, it creates an airflow over the aerofoil section. This flow can be considered to be moving in the opposite direction to the aerofoil movement (path), and is known as the relative airflow.
- **Angle of attack.** The angle between the chord line of an aerofoil and the relative airflow. Maximum aerofoil efficiency is obtained when the angle of attack is set to approximately 4 degrees.
- **Total reaction.** The total force brought about by the pressure difference between the upper and lower surfaces of an aerofoil when moved through the air.
- **Lift.** The component of the total reaction force which acts at right angles to the relative airflow.
- **Drag.** Drag is the resistance felt by a body when it is moved through the air. It is the component of the total reaction force which acts parallel to the direction of the airflow.
- **Plane of rotation.** The plane in which the propeller rotates, and is at right angles to the propeller axis.
- **Master station.** The position on the propeller blade where the blade angle is measured; it can be determined by measurement from the hub face. The master station is sometimes marked on the thrust face of the blade by a line drawn chordwise across the blade.
- **Blade angle.** The angle between the chord line of the blade and the plane of rotation of the propeller, measured at the master station.
- **Propeller torque.** The resistance to propeller rotation caused by the drag forces on the blades. It is the component of the total reaction which acts along the plane of rotation.
- **Disk area.** The area of the circle described by the propeller blade tips.
- **Blade path.** The path followed by the propeller blade whilst in flight. The direction of the blade path is determined by resolving the aircraft's forward and rotational velocity components and thus obtaining the actual direction of motion.
- **Blade track.** The path followed by the blades when the propeller is rotated with the aircraft in a stationary position. Each blade must follow the same track within narrow, prescribed limits.
- **Pitch.** The distance a propeller moves forward (advances) in one revolution. Pitch is subdivided as follows:
  a. **Geometric pitch.** The theoretical distance a propeller moves forward in one complete revolution when the blades are set at zero degrees angle of attack.

b. **Effective pitch.** The distance advanced by the propeller in one complete revolution after propeller slip has been taken into account.

- **Blade twist.** The tip of a propeller blade, being a greater distance from the propeller axis than the root, will travel at a greater speed than the root. To maintain an optimum (the most favourable) angle of attack, and to ensure that an even amount of thrust is generated from each section of the blade, the blade angle is progressively reduced towards the blade tip. This variation in the blade angle produces a helical shape known as the 'blade twist'.

- **Variable pitch.** The blade angle of some propellers can be adjusted, either manually or automatically, whilst the aircraft is in flight; these are known as 'variable pitch' propellers. The objective of a variable pitch propeller is to maintain the blade angle of attack at its optimum value over a wide range of engine power and forward speeds; thus maintaining maximum propeller efficiency.

- **Constant speed propeller.** A propeller, the pitch setting of which varies automatically to maintain a pre-selected constant rotational speed. The engine driving the propeller is most efficient over a narrow band of engine rpm; it therefore benefits the overall efficiency if the engine rpm is maintained within this band, over the range of aircraft forward speeds and engine power normally used. The variable pitch propeller enables this to be achieved by varying the load (propeller torque) to suit a particular value of speed and power, and presents the optimum blade angle necessary to efficiently absorb the available power, and convert it to thrust.

- **Constant speed unit.** The constant speed unit is an automatic governor which changes the blade angle to maintain a selected engine rpm when changes in forward speed occur.

- **Pitch range.** The angular range of blade pitch movement between the maximum fine and maximum coarse pitch settings.

- **Centrifugal twisting moment (CTM).** The centrifugal twisting moments are moments which act upon the blades of a propeller when it is rotating, and tend to turn the blades into fine pitch.

- **Aerodynamic turning movement (ATM).** The centre of pressure of a propeller blade aerofoil section is usually forward of the pitch change axis, and hence creates a turning moment which tends to turn the blades towards coarse pitch. This turning moment is known as the 'aerodynamic turning moment'; and never exceeds the value of the CTM.

- **Windmilling.** A propeller is said to be 'windmilling' when it is delivering power to the propeller shaft. If engine, or governor failure occurs, there is a danger that the CTM will turn the blades to a low pitch setting, and create a negative angle of attack, causing the propeller to 'windmill'. A windmilling propeller drives the engine, and can cause engine overspeeding to occur, with a consequent increase in aircraft drag, thus creating control difficulties.

- **Feathering pitch.** A pre-determined pitch setting which is selected to stop engine rotation, and to minimise drag when the engine is stopped in flight. When a propeller blade is turned to the feathered position, the chord line of the blades is approximately parallel to the direction of flight, and is used to prevent windmilling.

- **Static balance.** A propeller is said to be in static balance if, when concentrically mounted on a spindle supported by knife-edges, it will remain at rest in any position at any angle.

- **Dynamic balance.** A propeller is said to be in dynamic balance when the centrifugal forces due to its rotation do not produce an out-of-balance force or couple on the propeller shaft (ie the algebraic sum of the moments about the shaft are zero).

- **Aerodynamic balance.** A propeller is said to be in aerodynamic balance when the aerodynamic action on the blades results in no periodic forces or moments on the propeller mounting, and when each blade is producing an equal amount of thrust. Aerodynamic balance is achieved by adjusting the blade angles relative to each other during initial assembly of the propeller.
- **Solidity.** The ratio of the blade area to the disk area. The greater the solidity of the propeller, the greater the power that can be absorbed by it. Solidity may be determined by calculating the ratio between the sum of the blade chords at a given radius from the hub, and the circumference of the circle swept by these chords.
- **Propeller efficiency.** Efficiency, which is usually expressed as a percentage, may be sub-divided into three categories.:

  a. **Free air efficiency.** The ratio of the free air thrust horsepower to the torque horsepower.

  b. **Propulsive efficiency.** The ratio of the propulsive thrust horsepower to the torque horsepower.

  c. **Shaft efficiency.** The ratio of the shaft thrust horsepower to the torque horsepower.
- **Aspect ratio.** The ratio of the square of the span of a propeller blade to its gross area.
- **Vortex drag.** This is drag arising from the formation of trailing vortices from the propeller blade tips (formerly known as induced drag).

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