Introduction

Throughout the development of controlled flight as we know it, every aircraft required some kind of device to convert engine power to some form of thrust. Nearly all of the early practical aircraft designs used propellers to create this thrust.

As the science of aeronautics progressed, propeller designs improved from flat boards, which merely pushed the air backwards, to airfoil shapes. These airfoils produced lift to pull the aircraft forward through aerodynamic action.

As aircraft designs improved, propellers were developed which used thinner airfoil sections and had greater strength. Because of its structural strength, these improvements brought the aluminium alloy propeller into wide usage. The advantage of being able to change the propeller blade angle in flight led to wide acceptance of the two-position propeller and, later, the constant speed propeller system.

Today, propeller designs continue to be improved by the use of new composite materials, new airfoil shapes and multi blade configurations.

Terms

Before starting any discussion about propellers, it is necessary to define some basic terms to avoid confusion and misunderstanding.

A propeller is a rotating airfoil that consists of two or more blades attached to a central hub which is mounted on the engine crankshaft. The function of the propeller is to convert engine power to useful thrust. Propeller blades have a leading edge, trailing edge, a tip, a shank, a face, and a back as shown in Sub Module 17.2 "Propeller Construction" Figure 1 on page 2.

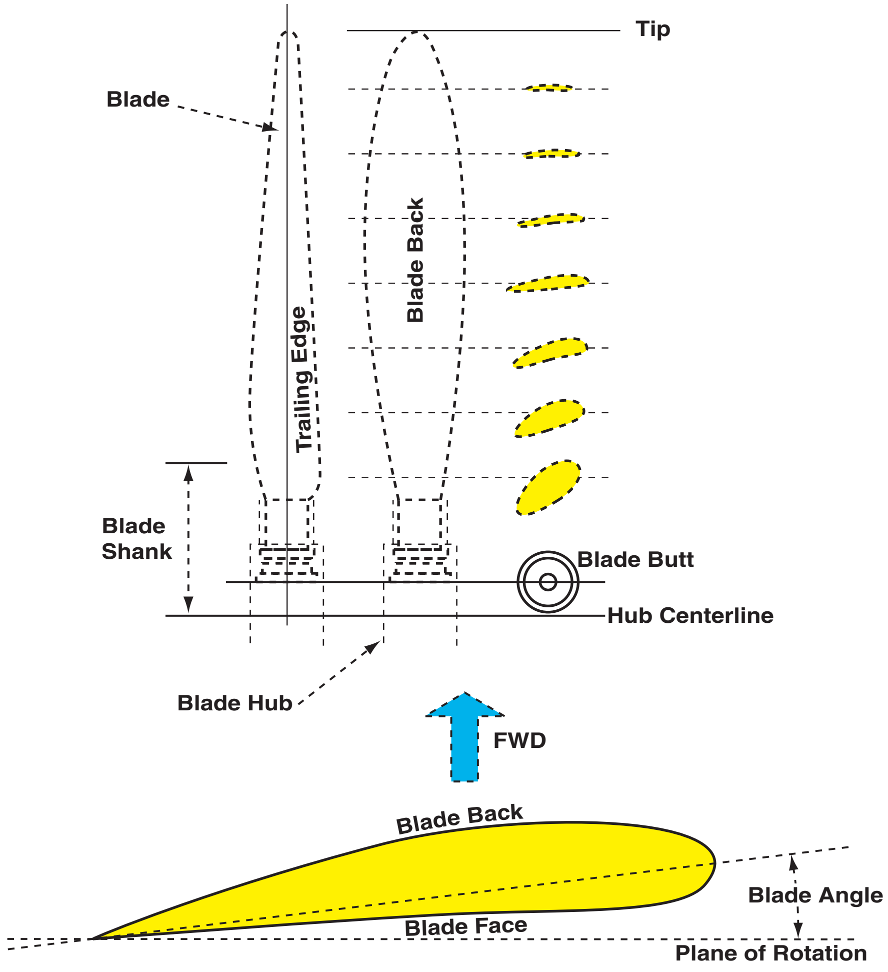
Blade angle is the angle between the propeller's plane of rotation, and the chord line of the propeller airfoil.

Blade station is a reference position on a blade that is a specified distance from the cen ter of the hub.

Pitch is the distance (in inches or milimetres) that a propeller section will move forward in one revolution.

Pitch distribution is the gradual twist in the propeller blade from shank to tip.

Figure 1: Propeller Terms



Blade Element Theory

The thrust produced by a propeller blade is determined by five things: the shape and area of the airfoil section, the angle of attack, the density of the air, and the speed at which the airfoil moves through the air.

Before discussing ways of varying the amount of lift produced by a propeller blade, we must understand some of the propeller design characteristics.

The blade element theory considers a propeller blade to be made of an infinite number of airfoil sections, with each section located a specific distance from the axis of rotation of the propeller. Each blade element travels at a different speed because of its distance from the centre of the hub, and to prevent the thrust from increasing along the length of the blade as its speed increases, the cross-sectional shape of the blade and its blade, or pitch, angle, vary from a thick, high pitch angle near the low-speed shank to a thin, low pitch angle at the high-speed tip.

By using the blade element theory, a propeller designer can select the proper airfoil section and pitch angle to provide the optimum thrust distribution along the blade. This is named propeller twist.

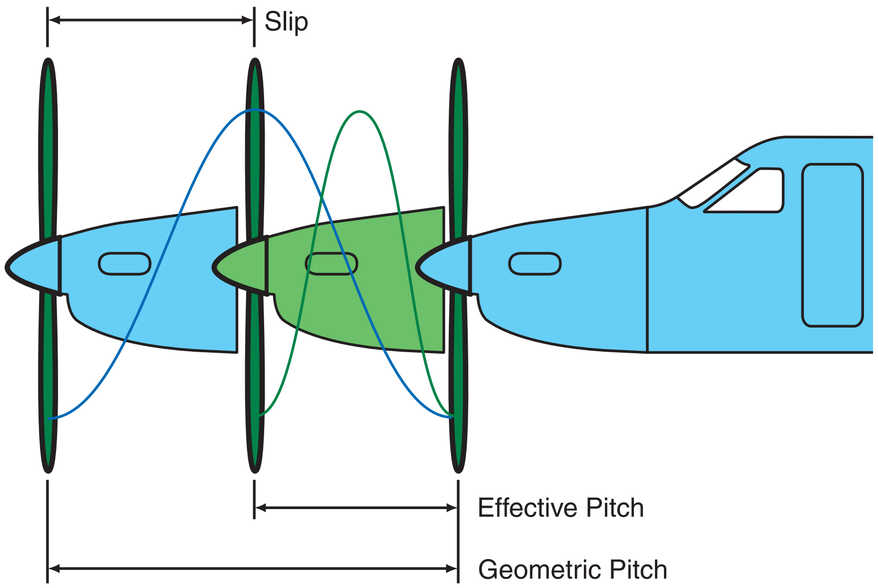
The thrust developed by a propeller is in accordance with Newton's third law of motion. (For every action there is an equal and opposite reaction). In the case of a propeller, the first action is the acceleration of a mass of air to the rear of the aircraft. The reaction is that the aeroplane is pulled forward.

Since the angle of a propeller blade varies along its length, a particular blade station must be chosen to specify the pitch of a blade.

Rather than using blade angles at a reference station, some propeller manufacturers express pitch in inches at 75% of the radius. This is the geometric pitch, or the distance this particular element would move forward in one revolution along a helix, or spiral, equal to its blade angle.
The effective pitch is the actual distance a propeller advances through the air in one revolution. This cannot be determined by the pitch angle alone because it is affected by the forward velocity of the airplane.

The difference between geometric and effective pitch is called propeller slip.
If a propeller has a pitch of 50 inches, in theory it should move forward 50 inches in one revolution. But if the aircraft actually moves forward only 35 inches in one revolution the effective pitch is 35 inches and the propeller efficiency is 70%.

Figure 2: Propeller Slip



Angle of Attack

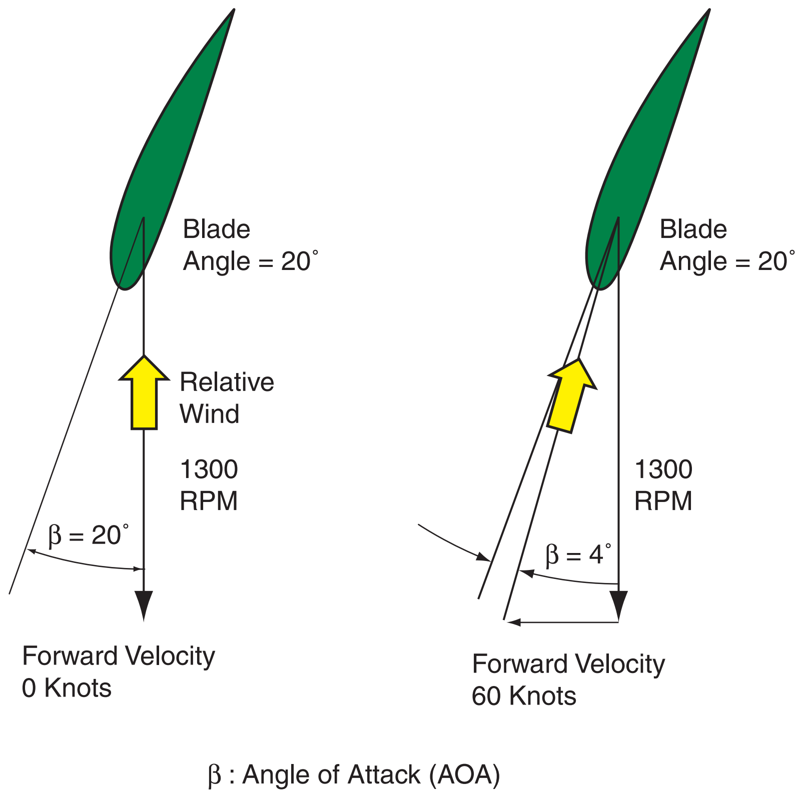
Thrust produced by a propeller, in the same way as lift produced by a wing, is determined by the blade's angle of attack. It is the acute angle between the chord line of a propeller blade and the relative wind.

Angle of attack relates to the blade pitch angle, but it is not a fixed angle. It varies with the forward speed of the airplane and the RPM of the propeller.

As an example: When there is no forward speed, angle of attack (α) and blade pitch angle are the same, 20°.

When the airplane is moving forward at 60 knots, angle of attack becomes much less than the blade pitch angle (see "Figure 3" on page 4).

Figure 3: Propeller Angle of Attack



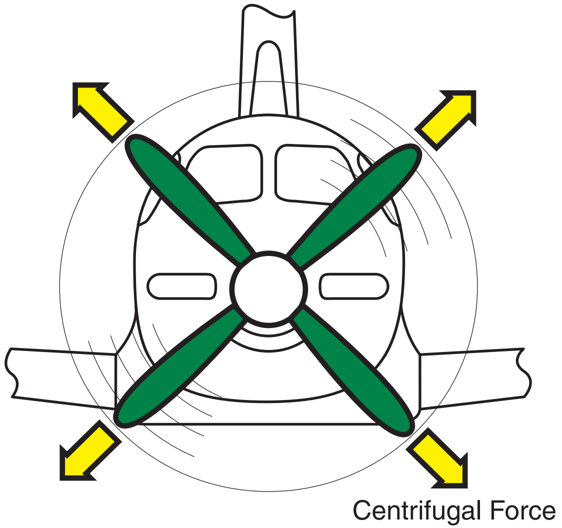
Forces Acting on the Propeller

When a propeller rotates, many forces interact and cause tension, twisting, and bending stresses within the propeller.

Centrifugal Force

Centrifugal force puts the greatest stress on a propeller as it tries to pull the blades out of the hub. It is not uncommon for the centrifugal force to be several thousand times the weight of the blade. For example, a 10 kg propeller blade turning at 2,700 RPM may exert a force of 50 tons on the blade root.

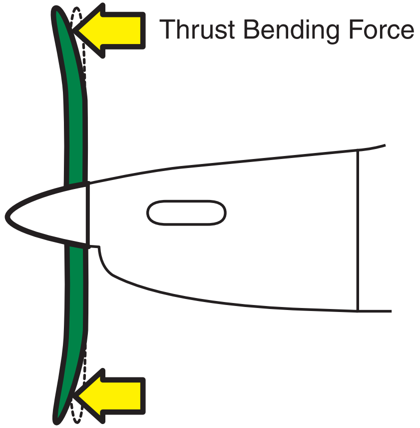
Figure 4: Propeller Centrifugal Force



Thrust Bending Force

Thrust bending force attempts to bend the propeller blades forward at the tips, because the lift toward the tip of the blade flexes the thin blade sections forward. Thrust bending force opposes centrifugal force to some degree.

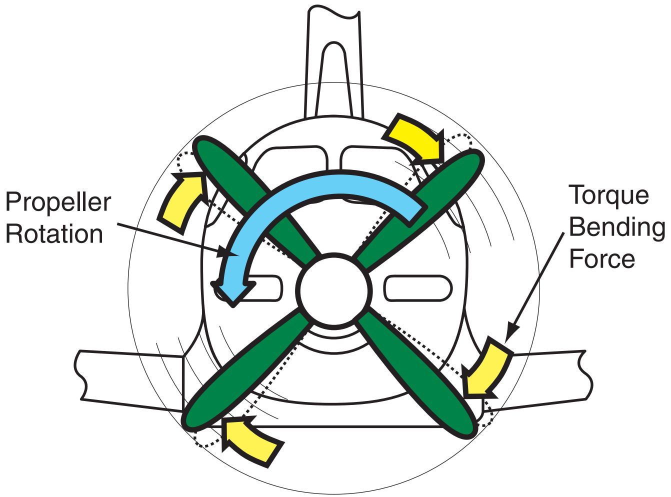
Figure 5: Thrust Bending Force



Torque Bending Force

Torque bending forces try to bend the propeller blade back in the direction opposite the direction of rotation.

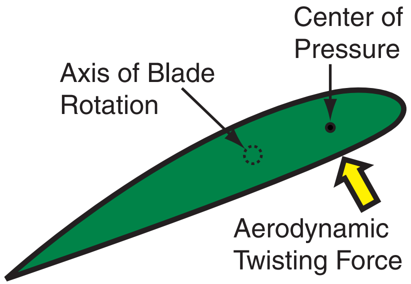
Figure 6: Propeller Torque Bending Force



Aerodynamic Twisting Moment

Aerodynamic twisting moment tries to twist a blade to a higher angle. This force is produced because the axis of rotation of the blade is at the midpoint of the chord line, while the centre of the lift of the blade is forward of this axis. This force tries to increase the blade angle. Aerodynamic twisting moment is used in some designs to help feather the propeller.

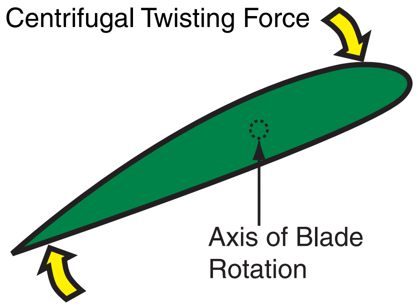
Figure 7: Propeller Aerodynamic Twisting Moment



Centrifugal Twisting Moment

Centrifugal twisting moment tries to decrease the blade angle, and opposes aerodynamic twisting moment. This tendency to decrease the blade angle is produced since all the parts of a rotating propeller try to move in the same plane of rotation as the blade centerline. This force is greater than the aerodynamic twisting moment at operational RPM and is used in some designs to decrease the blade angle.

Figure 8: Propeller Centrifugal Twisting Moment



Vibrational Forces and Resonance

When a propeller is producing thrust, aerodynamic and mechanical forces are present which cause the blades of the propeller to vibrate (see “Figure 9” on page 7). A person designing a propeller must take this into consideration. If this is not done, these vibrations may cause excessive flexing, hardening of the metal and could result in sections of the propeller breaking off during operation.

Aerodynamic forces have a great vibration effect at the tip of the blade where the effects of transonic speeds cause buffeting and vibrations.

Mechanical vibrations are caused by power pulses in a piston engine and are more destructive then aerodynamic vibrations. The most critical location when looking for the stresses is about 2.5 cm from the propeller tip.

Most airframe-engine-propeller combinations have no problem in eliminating the effects of vibrational stresses. However some combinations are sensitive to certain RPM ranges and they have a critical range indicated on the tachometer by a red arc. The engine should not be operated in this range. If it is operated in the critical range over a period of time, there is a strong possibility that the propeller will suffer from structural failure due to the vibrational stresses.

Figure 9: Propeller Vibration