XII. PROPELLER

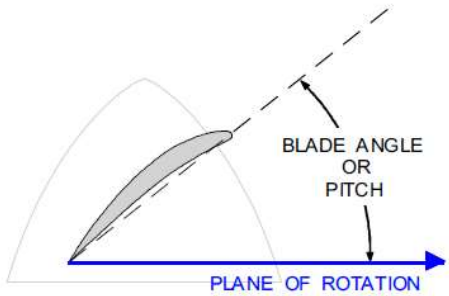
A propeller converts shaft power from the engine into thrust. It does this by accelerating a mass of air rearwards when creating a forward aerodynamic force by the blades, the **THRUST**. Thrust from the propeller is equal to the mass of air accelerated rearwards multiplied by the acceleration given to it. A mass is accelerated rearwards and the equal and opposite reaction drives the aircraft forwards.

1) Description & Definitions

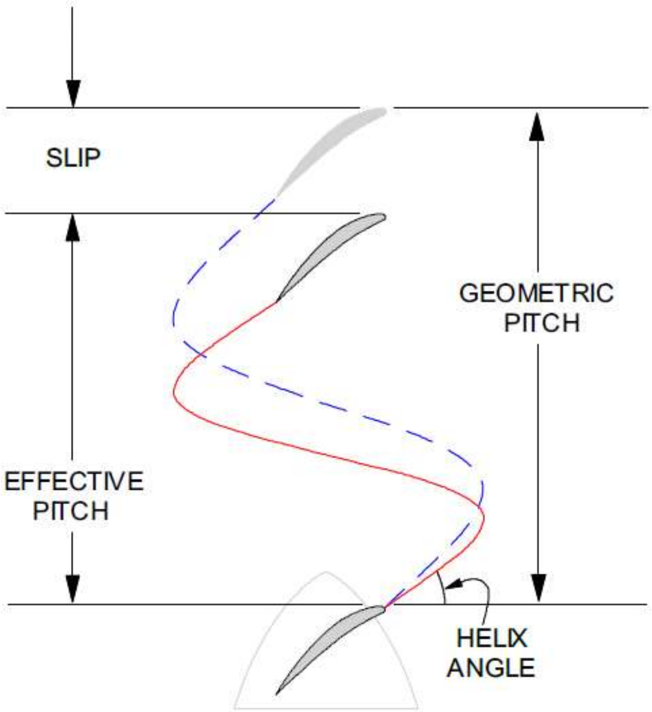
The propeller blade is an aerofoil and the definitions for chord, camber, thickness/chord ratio and aspect ratio are the same as those given previously for the wing. It is a "rotating wing" and its forward LIFT is actually its THRUST. Additionally the following must be considered.

<u>BLADE ANGLE or PITCH</u>

The angle between the blade chord and the plane of rotation. Blade angle decreases from the root to the tip of the blade (twist) because rotational velocity of the blade increases from root to tip. For reference purposes, the blade angle is measured at a point 75% of the blade length from the root.



2) Geometric Pitch & Effective Pitch



<u>GEOMETRIC PITCH</u>

The geometric pitch is the distance the propeller would travel forward in one complete revolution if it were moving through the air at the blade angle.

<u>EFFECTIVE PITCH</u>

In flight the propeller does not move through the air at the geometric pitch, the distance it travels forward in each revolution depends on the aircraft's forward speed. The distance which it actually moves forward in each revolution is called the "effective pitch" or "advance per revolution".

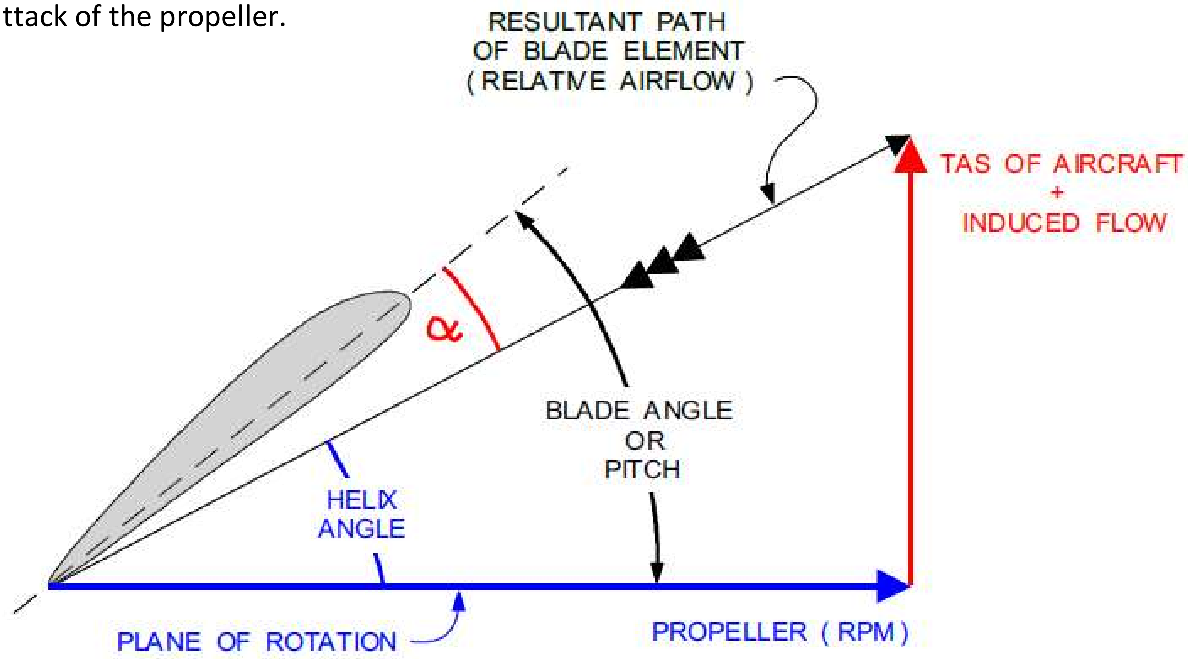
<u>PROPELLER SLIP</u>

The difference between the Geometric and the Effective Pitch is called the Slip.

HELIX ANGLE
The angle that the actual path of the propeller makes to the plane of rotation.

ANGLE OF ATTACK
The path of the propeller through the air determines the direction of the relative airflow.
The angle between the blade chord and the relative airflow is the angle of attack (α).
The angle of attack (α) is the result of propeller rotational velocity (RPM) and aircraft forward velocity (TAS).

In a "fixed pitch" propeller (picture below) at constant RPM, increasing TAS decreases the angle of attack of the propeller. At a constant TAS, increasing RPM increases the angle of attack of the propeller.



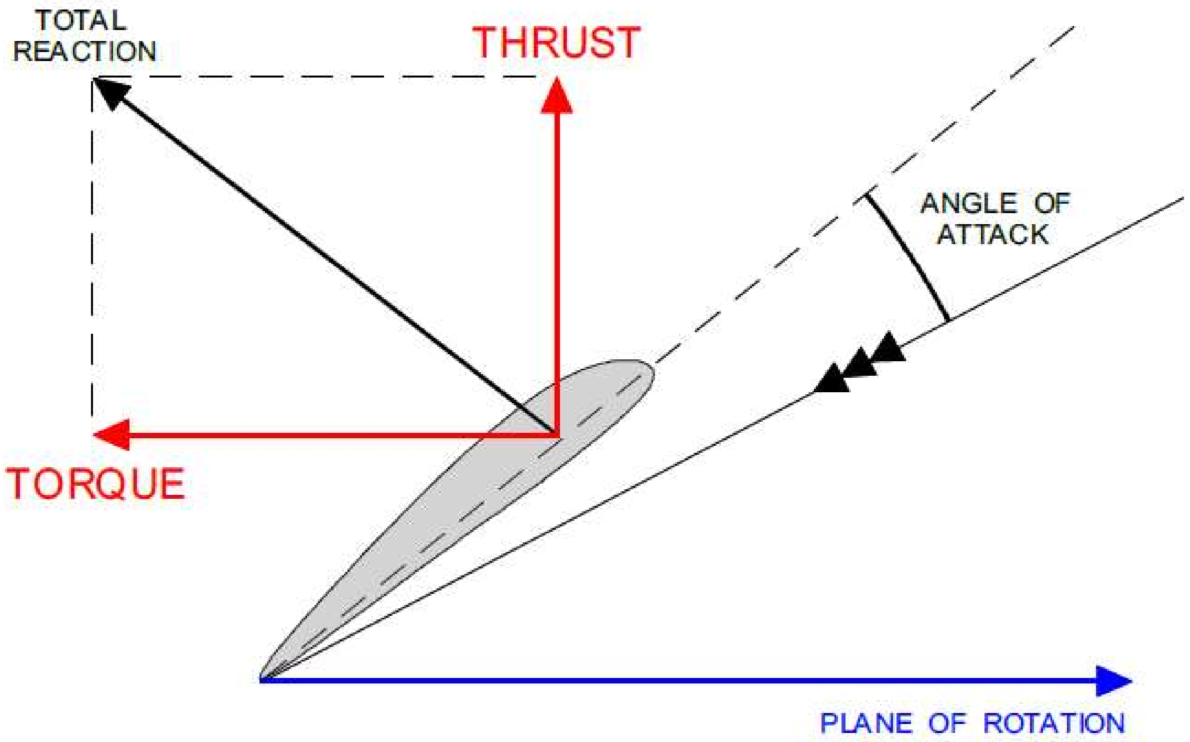
3) Propeller Mechanics

AERODYNAMIC FORCES ON THE PROPELLER
A propeller blade has an aerofoil section, and when moving through the air at an angle of attack will generate aerodynamic forces in the same way as a wing. The shape of the section will generate a pressure differential between the two surfaces. The surface which has the greater pressure is called the "pressure face" or "thrust face". When the propeller is giving forward thrust, the thrust face is the rear, (flat) surface. The pressure differential will generate an aerodynamic force, the total reaction, which may be resolved into two components, thrust and propeller torque.

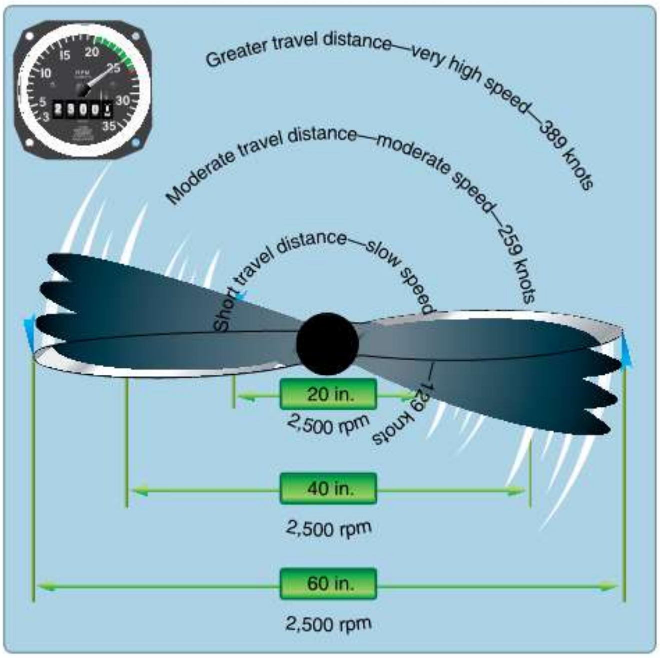
THRUST
A component at right angles to the plane of rotation. The thrust force will vary along the length of each blade, reducing at the tip where the pressures equalise and towards the root where the rotational velocity is low. <u>Thrust will cause a bending moment on each blade, tending to bend the tip forward</u>. (Equal and opposite reaction to "throwing" air backwards).

TORQUE (Propeller)

The equal and opposite reaction to being rotated, which generates a turning moment about the aircraft longitudinal axis. Propeller torque also gives a bending moment to the blades in, but in the opposite direction to, the plane of rotation.

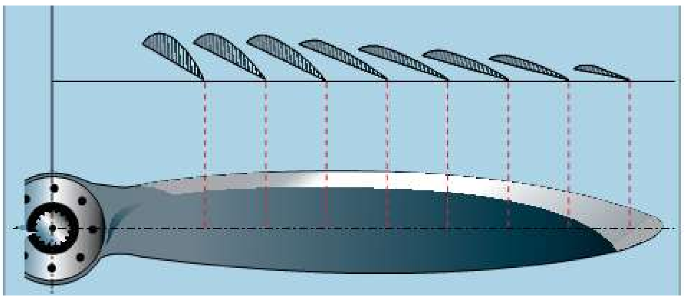


BLADE TWIST



The blade accelerate the airmass to generate THURST at a given angle of attack. To maintain a constant THURST along the blade, since the tip travels at a faster speed than the root, the angle of attack at the tip will be higher and the THURST won't be constant along the blade, eventually the tip could stall and become inefficient. So to maintain a constant angle of attack and so a constant THURST along the blade, the blade is twisted so its angle decreases from the root to the tip.

For reference, the blade angle is measured at a point 75% of the blade length from the root.



4) Propeller Efficiency

The efficiency of the propeller can be measured from the ratio, Power out / Power in. The power extracted (out) from a propeller "Thrust Power" is the product of Force (Thrust) x Velocity (TAS). The power into the propeller "Shaft Power" is engine torque (Force) x Rotational Velocity (RPM). The efficiency of the propeller can be expressed as:

$$\boldsymbol{Propeller\ Efficiency = \frac{Thrust\ Power}{Shaft\ Power}}$$

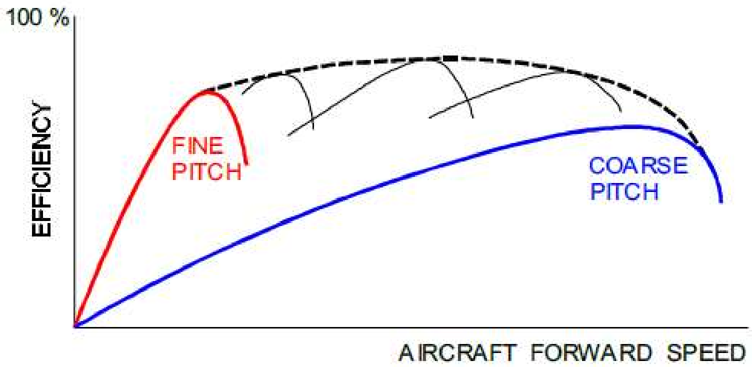
VARIATION OF PROPELLER EFFICIENCY WITH SPEED

A) Fixed Pitch Propeller

In a fixed pitch propeller, increasing TAS at a constant RPM reduces the blade angle of attack. This will decrease thrust. The effect of this on propeller efficiency is as follows:

- At some high forward speed the blade will be close to zero lift angle of attack and thrust, and therefore Thrust Power, will be zero. From the above 'equation' it can be seen that propeller efficiency will also be zero.
- There will be only one speed at which a fixed pitch propeller is operating at its most efficient angle of attack and where the propeller efficiency will be maximum
- As TAS is decreased, thrust will increase because blade angle of attack is increased. Thrust is very large, but the TAS is low so propeller efficiency will be low. Thus no useful work is being done when the aircraft is, for instance, held against the brakes at full power prior to take-off. The efficiency of a fixed pitch propeller varies with forward speed

If blade angle can be varied as TAS and/or RPM is changed, the propeller will remain efficient over a much wider range of aircraft operating conditions



Fine Pitch: Low angle of blade
For T/O, Climb and LDG

Coarse Pitch: High angle of blade
For CRUISE

B) **Variable Pitch Propellers**

a) **Adjustable pitch propellers:**

These are propellers which can have their pitch adjusted on the ground by mechanically re-setting the blades in the hub. In flight they act as fixed pitch propellers.

b) **Two pitch propellers:**

These are propellers which have a fine and coarse pitch setting which can be selected in flight. Fine pitch can be selected for take-off, climb and landing and coarse pitch for cruise. They will usually also have a feathered position.

c) **(Variable pitch) Constant speed propellers:**

Modern aircraft have propellers which are controlled automatically to vary their pitch (blade angle) so as to maintain a selected RPM. A variable pitch propeller permits high efficiency to be obtained over a wider range of TAS, giving improved take-off and climb performance and cruising fuel consumption.

CONSTANT SPEED PROPELLER

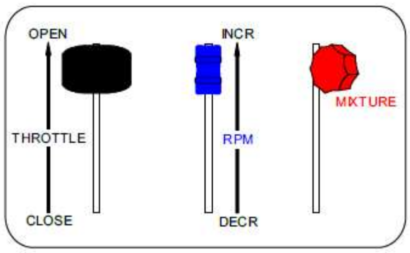


Illustration a "typical" set of engine and propeller controls for a small piston engine aircraft with a variable pitch propeller. Throttle, prop' and mixture are shown in the take-off. (all forward) position.

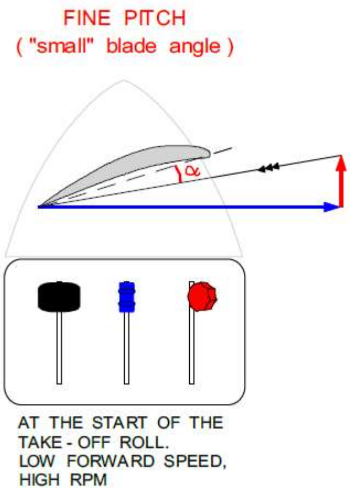
"Pulling back" on the prop' control will decrease RPM.

"Pushing forward" on the prop' control will increase RPM.

NB: A reasonable analogy is to think of the prop' control as an infinitely variable "gear change".

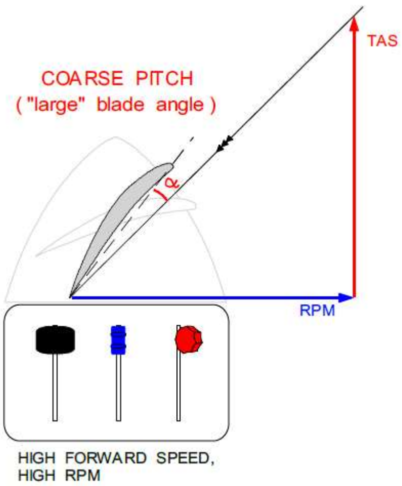
Forward (increase RPM) is first gear.

Back (decrease RPM) is fifth gear.



FINE PITCH

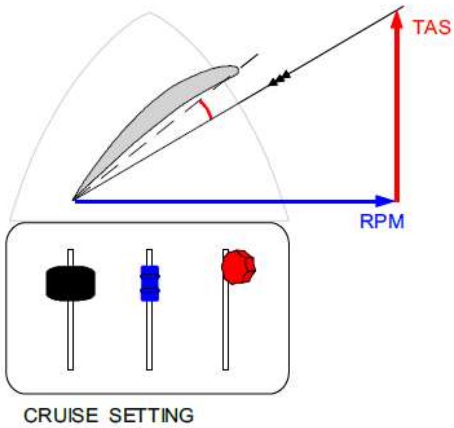
During the early stages of take-off roll. The RPM is set to maximum and the TAS is low. The angle of attack is optimum and maximum available efficiency is obtained. As the aircraft continues to accelerate the TAS will increase, which decreases the angle of attack of the blades. Less thrust will be generated and less propeller torque. This gives less resistance for the engine to overcome and RPM would tend to increase. The constant speed unit (CSU) senses the RPM increase and increases pitch to maintain the blade angle of attack constant.

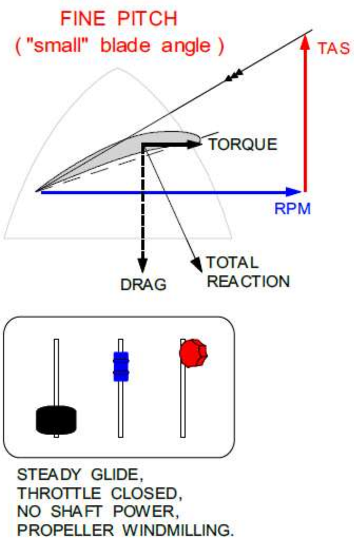


COARSE PITCH

At high forward speed in level flight. As the TAS increased, the CSU continually increased the blade angle (coarsened the pitch) to maintain a constant blade angle of attack.

When the engine and prop' have been set for cruise conditions. Optimum throttle and RPM setting are listed in the aircraft Flight Manual. The recommended procedure is to reduce the throttle first, then RPM. Whatever configuration into which the aircraft is placed, climb, descent or bank, the CSU will adjust the blade angle (prop' pitch) to maintain the RPM which has been set. At least it will try to maintain constant RPM. There are exceptions, which will be discussed during flight training.

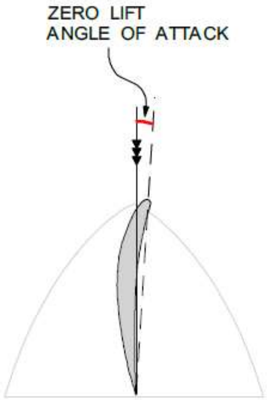




WINDMILLING

If a loss of engine torque occurs (the throttle is closed or the engine fails), the prop' will "fine off" in an attempt to maintain the set RPM. The relative airflow will impinge on the front surface of the blade and generate drag and "negative propeller torque". The propeller will now drive the engine.

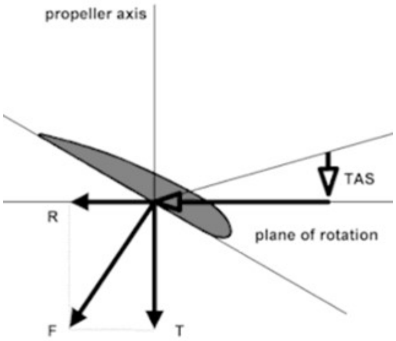
The drag generated by a windmilling propeller is very high.



FEATHERING

Following an engine failure on a twin engine aeroplane the increased drag from the windmilling propeller will seriously degrade climb performance, limit range and add to the yawing moment caused by the failed engine which will affect controllability. Also, by continuing to turn a badly damaged engine, eventual seizure of the engine or an engine fire might result.

By turning the blades to their zero lift angle of attack, no propeller torque is generated and the propeller will stop, reducing drag to a minimum.



REVERSE

Another angle exist in some aeroplanes, is the REVERSE PITCH. The reverse pitch is to create a backward thrust, known as **REVERSE THRUST**, and this is used to assist the brakes during the landing and to shorten the landing distance by creating more deceleration.

The pitch is simply reduced to a negative angle of blade and generate a negative thrust.

5) Power Absorption

A propeller must be able to absorb all the shaft power developed by the engine and also operate with maximum efficiency throughout the required performance envelope of the aircraft.

This can be done by increasing the diameter of the propeller, however the critical factor is tip velocity. If tip velocity is too high the blade tips will approach the local speed of sound and compressibility effects will decrease thrust and increase rotational drag.

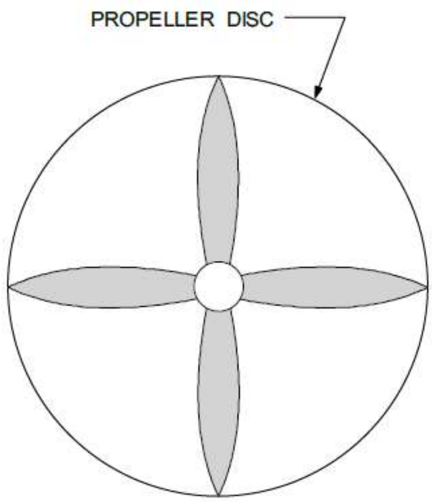
Supersonic tip speed will considerably reduce the efficiency of a propeller and greatly increase the noise it generates.

This imposes a limit on propeller diameter and RPM, and the TAS at which it can be used.

Other limitations on propeller diameter are the need to maintain adequate ground clearance and the need to mount the engines of a multi-engine aircraft as close to the fuselage as possible to minimise the thrust arm. Increasing the propeller diameter requires the engine to be mounted further out on the wing to maintain adequate fuselage clearance. To keep V_{MC} within acceptable limits the available rudder moment would have to be increased. Clearly, increasing the propeller diameter to increase power absorption is not the preferred option.

SOLIDITY

To increase power absorption several characteristics of the propeller can be adjusted. The usual method is to increase the "solidity" of the propeller. Propeller solidity is the ratio of the total frontal area of the blades to the area of the propeller disc. It can be seen from the Figure that an increase in solidity can be achieved by:



- **Increasing the chord of each blade.**

This increases the solidity, but blade aspect ratio is reduced, making the propeller less efficient (increase tip induced drag)

- **Increasing the number of blades.**

Power absorption is increased without increasing tip speed or reducing the aspect ratio. Increasing the number of blades beyond a certain number (five or six) will reduce overall efficiency.

Thrust is generated by accelerating air rearwards. Making the disk too solid will reduce the mass of air that can be drawn through the propeller and accelerated. To increase the number of blades efficiently, two propellers rotating in opposite directions on the same shaft are used. These are called: **contra-rotating propellers**.

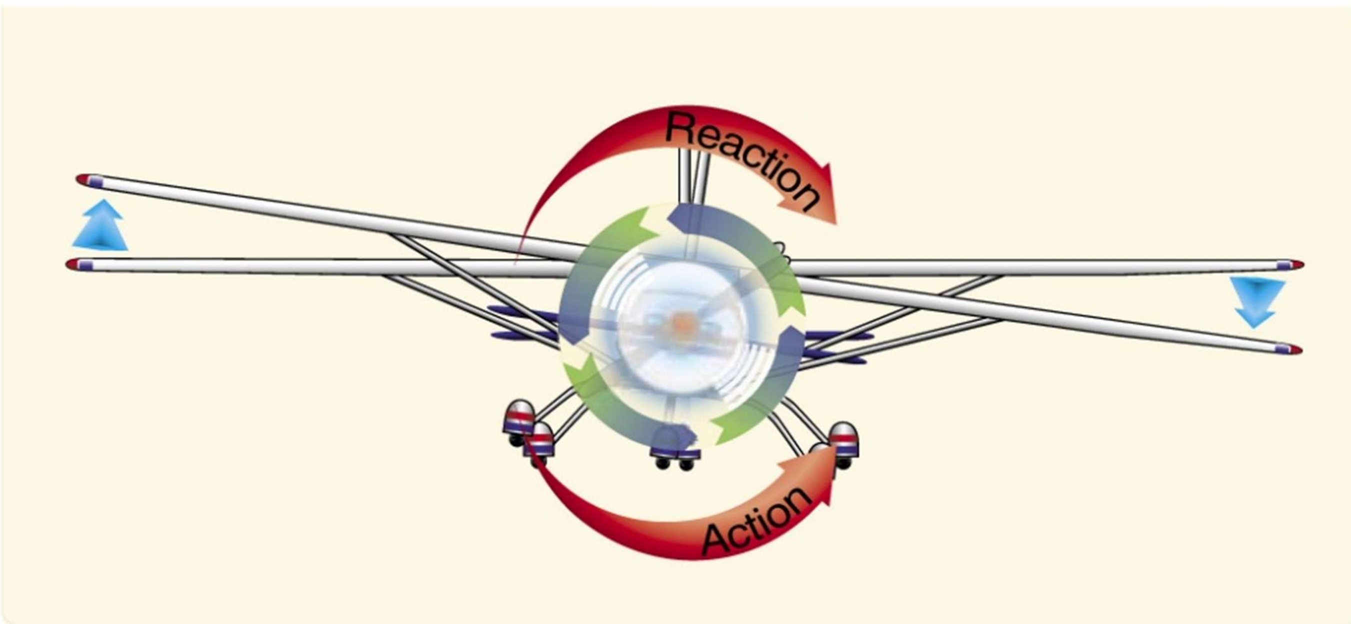
6) Moments & Forces generated from a propeller

Note: The majority of modern engines are fitted with propellers which rotate clockwise when viewed from the rear, so called "right-hand" propellers. The exceptions are small twin piston engine aircraft which often have the propeller of the right engine rotating anti-clockwise to eliminate the disadvantage of having a "critical engine" (seen later) plus some older aircraft.

Due to its rotation a propeller generates yawing, rolling and pitching moments. These are due to several different causes:

TORQUE REACTION ***(The propeller is turning right/clockwise from the pilot view)***
Because the propeller rotates clockwise, the equal and opposite reaction (torque) will give the aircraft an anti-clockwise rolling moment about the longitudinal axis. During take-off this will apply a greater down load to the left wheel, causing more rolling resistance on the left wheel making the aircraft want to yaw to the left. In flight, torque reaction will also make the aircraft want to roll to the left. **Torque reaction will be greatest during high power (RPM), low airspeed (IAS) flight conditions.** Low IAS will reduce the power of the controls to counter the "turning" moment due to torque.

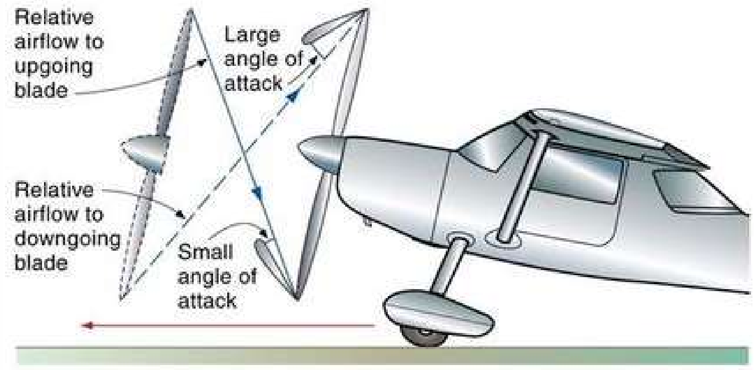
Torque reaction can be eliminated by fitting contra-rotating propellers. Torque from the two propellers, rotating in opposite directions on the same shaft, will cancel each other out. Co-rotating propellers on a small twin will not normally give a torque reaction until one engine fails. A left "turning" tendency would then occur. Counterrotating propellers on a small twin will reduce the torque reaction following an engine failure.

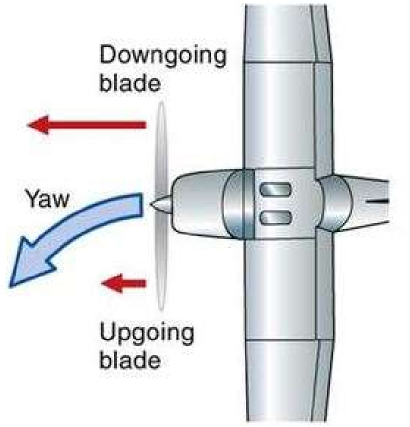


ASYMMETRIC BLADE EFFECT or P-FACTOR

In general the propeller shaft will be inclined upwards from the direction of flight due to the angle of attack of the aircraft. This gives the down going propeller blade a greater effective angle of attack than the up going blade. The down going (right) blade will generate more thrust. The difference in thrust on the two sides of the propeller disc will give a yawing moment to the left with a clockwise rotating propeller in a nose-up attitude.

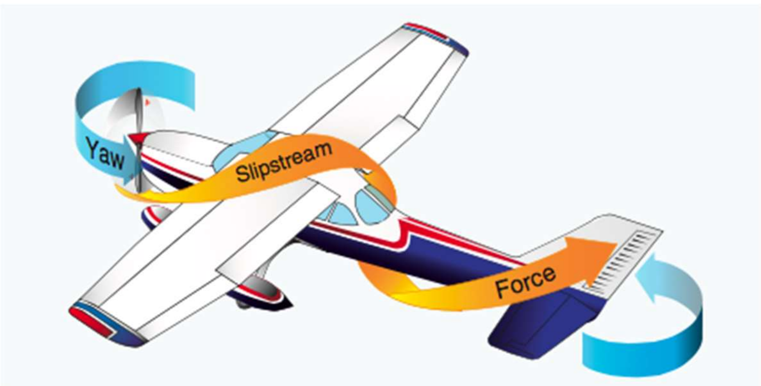
Asymmetric blade effect will be greatest at high power (RPM) and low airspeed (high angle of attack).





SPIRAL SLIPSTREAM EFFECT

As the propeller rotates it produces a backward flow of air, or slipstream, which rotates around the aircraft. This spiral slipstream causes a change in airflow around the fin (vertical stabiliser). Due to the direction of propeller rotation (clockwise) the spiral slipstream meets the fin at an angle from the left, producing a sideways force on the fin to the right.



Spiral slipstream effect gives the aircraft a yawing moment to the left.

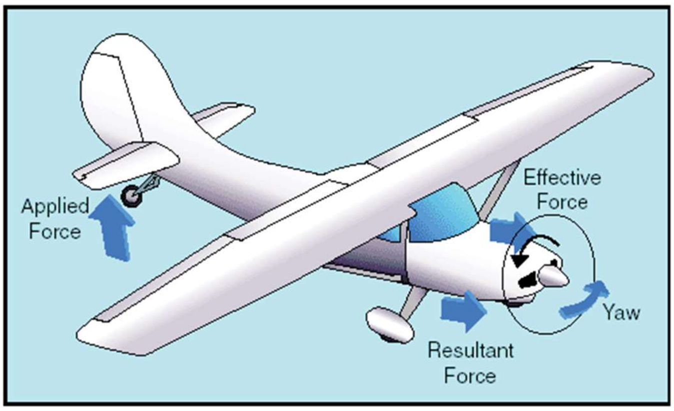
The amount of rotation given to the air will depend on the throttle and RPM setting.

Spiral slipstream effect can be reduced by:

- the use of contra or counter rotating propellers,
- a small fixed tab on the rudder,
- the engine thrust line inclined slightly to the right,
- or offsetting the fin slightly.

GYROSCOPIC EFFECT

A rotating propeller has the properties of a gyroscope - rigidity in space and precession. The characteristic which produces "gyroscopic effect" is precession. Gyroscopic precession is the reaction that occurs when a force is applied to the rim of a rotating disc. When a force is applied to the rim of a propeller the reaction occurs 90° ahead in the direction of rotation, and in the same direction as the applied force. As the aircraft is pitched up or down or yawed left or right, a force is applied to the rim of the spinning propeller disc.



Note: Gyroscopic effect only occurs when the aircraft pitches and/or yaws.

For example, if an aircraft with a clockwise rotating propeller is pitched nose up, imagine that a forward force has been applied to the bottom of the propeller disc. The force will "emerge" at 90° in the direction of rotation, i.e. a right yawing moment. Gyroscopic effect can be easily determined when the point of application of the imagined forward force on the propeller disc is considered.

Pitch down - forward force on the top, force emerges 90° clockwise, left yaw.

Pitch up - forward force on the bottom, force emerges 90° clockwise, right yaw.

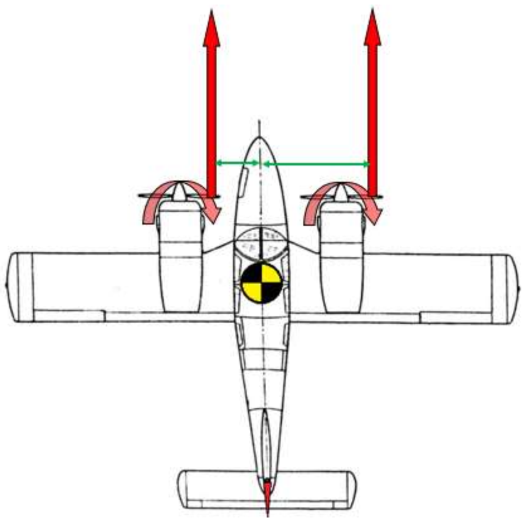
Left yaw - forward force on the right, force emerges 90° clockwise, pitch up.

Right yaw - forward force on the left, force emerges 90° clockwise, pitch down.

Gyroscopic effect will be cancelled if the propellers are contra rotating.

7) Critical Engine

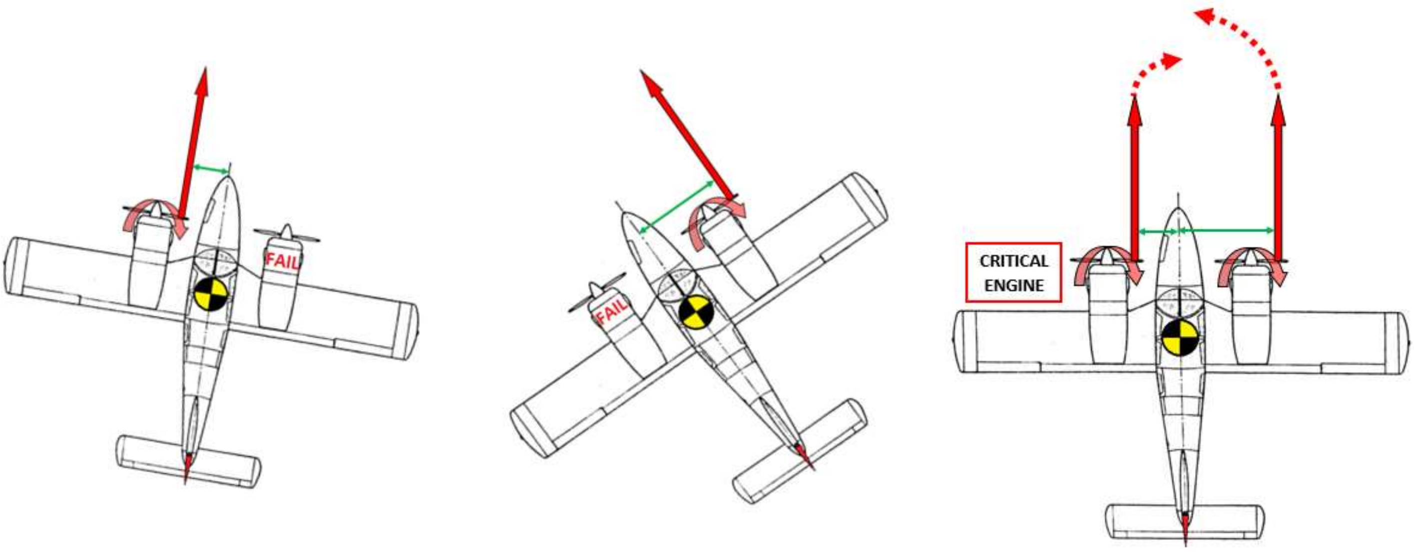
In a multiengine aircraft, in the event of one engine failure, the aircraft will experience an yaw followed by a roll moment toward the failed engine due to the differential thrust.



However, since the propeller generates more thrust from the downgoing blade than the upgoing blade (P-FACTOR/ASSYMETRIC BLADE). For a clockwise rotation propeller, the thrust line will be from the right side of the propeller.

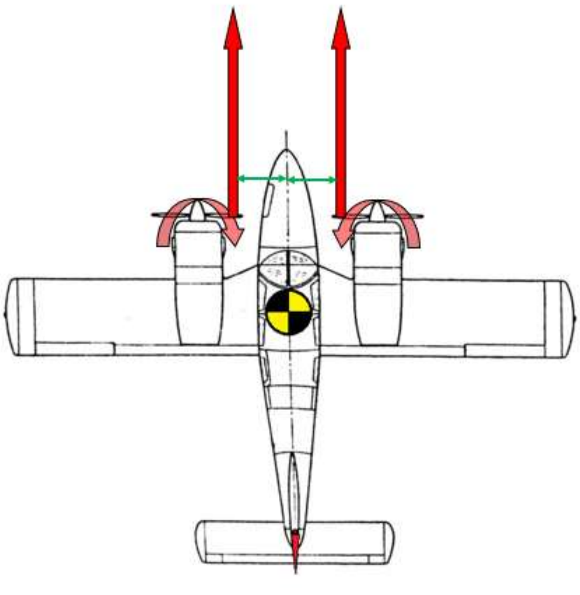
In that case, for co-rotation engines (same direction), on the right engine of the aircraft, the thrust line has a bigger arm from the aircraft's CG than the thrust on the left engine of the aircraft.

If the right engine fails there will be a yawing and rolling moment to the right, and the pilot must counteract for those moments by pushing on the left rudder pedal and deflecting the stick to the left. However if the left engine fails, the moments generated will be much higher, and the corrective action from the pilot will be much more significant, so the station is much more critical. Since the left engine will make the situation much more critical, so we say that the left engine is the **CRITCAL ENGINE**.



<u>Note</u>: If the engines are co-rotation right, the critical engine is the LEFT ENGINE, and if the engine are co-rotation left, the critical engine is the RIGHT ENGINE.
The situation will be worse when there is a cross-wing from the same side of the critical engine if this one failed, since the yawing and rolling moment are toward the failed engine, the cross-wind from the that side will push on the fin and increase further the yawing moment (i.e. critical engine left and crosswind from the left)

<u>No Critical Engine</u>
On the light twinjet aircrafts, the propeller are counterrotating (oppsite direction) in such a way the thurst line is closer and on the same distance to aircraft's CG. This means that in the event of a failure if any engine, the ywaming and rolling moment will be the least from any engine.
The disavantage of the counterrotating propellers, is that the left propeller doesn't fit the right engine and vice-versa, thus increasing the maintenance costs.



8) Effect of Atmospheric Conditions

Changes of atmospheric pressure or temperature will cause a change of air density. This will affect:

- the power produced by the engine at a given throttle position and
- the resistance to rotation of the propeller (its drag).

An increase in air density will increase both the engine power and the propeller drag. **The change in engine power is more significant than the change in propeller drag.**

ENGINE AND PROPELLER COMBINED

If the combined effect of an engine and propeller is being considered, it is the engine power change which will determine the result. For an engine driving a fixed pitch propeller:

- if density increases, RPM will increase.
- if density decreases, RPM will decrease.

ENGINE ALONE

If the shaft power required to drive the propeller is being considered, then it is only the propeller torque which needs to be taken into account. To maintain the RPM of a fixed pitch propeller:

- if density increases, power required will increase,
- if density decreases, power required will decrease.