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AERODYNAMICS 2

CHAPTER 5 – PROPELLERS

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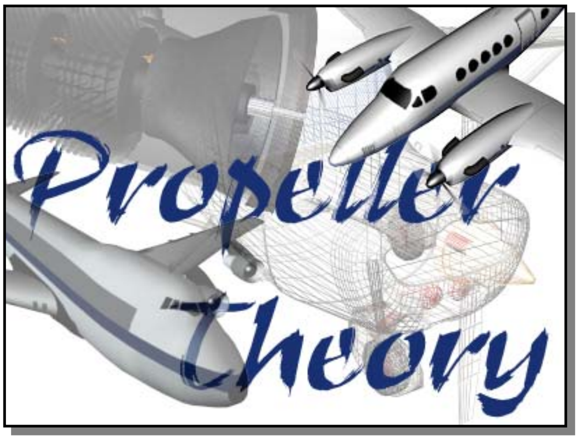
CONTENTS .... PAGE

BASIC PRINCIPLES OF PROPELLER THEORY

INTRODUCTION



Of all the various systems of propulsion, the propeller was the most used in the past and it is likely that it will still be used to a great extent in the future.

Due to the low power output of the first jet engines, large aircraft such as bombers and airliners were still propeller driven until the late 1950's, early 1960's.

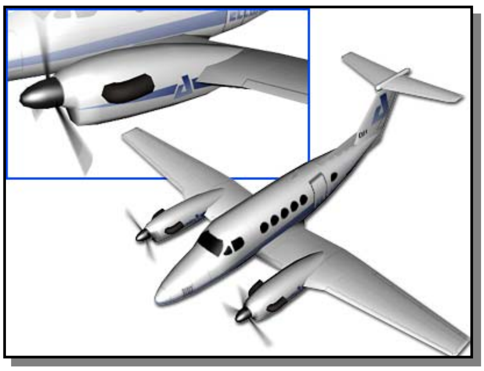
Many modern aircraft are still driven by propellers and research is being carried out in the area of the "Ultra High Bypass Turbofan" or "Unducted Fan" which is in effect a high speed propeller capable of high subsonic speeds.

In modern aircraft the propeller is often driven by a gas turbine instead of a piston engine. However, the basic aerodynamic principles remain the same, regardless of the type of power source.

A **turbojet** produces thrust solely from the jet efflux which imparts a large acceleration to a small air mass. T = MA (thrust = mass x velocity)

Efficiency of Propulsion $\propto \dfrac{1}{(\text{Velocity of efflux})^2}$

The efficiency of any propulsive system is inversely proportional to the square of the velocity of the efflux or slipstream. As speed increases, propellers lose efficiency, and turbofans or turbojets are used.



With a **turboprop**, a small air mass is accelerated to a high velocity that drives a power turbine. The power turbine is coupled to the propeller that in turn imparts a smaller acceleration to a larger air mass. T=MA.

With a bypass turbofan the air mass is divided. A small part of the air mass is accelerated to a high velocity and drives a large fan through which the larger part is passed and accelerated to a lower velocity.

A bypass- or fan engine can be considered as halfway between a turbojet and turboprop.

CATEGORIES OF PROPELLERS

Generally propellers can be divided into three categories:

FIXED PITCH

As the name suggests, the “Pitch” of this type of propeller cannot be changed. The early wooden propellers, and even the first metal propellers, were of the fixed pitch type.

A fixed pitch propeller achieves maximum efficiency only under certain conditions.

Very few modern aircraft still make use of fixed pitch propellers.

This type of propeller is mostly used on ultra-light aircraft such as micro-lights and some motorized gliders due to the obvious weight penalties if more complex type propellers are used.

VARIABLE PITCH (PISTON ENGINE)

The first advance from the fixed pitch propeller was a variable pitch propeller with two or three settings for different speeds or altitudes.

Modern variable pitch propellers can be governed in flight to **any RPM** selected by the pilot.

Some variable pitch propellers on piston engine aircraft also have feathering and reverse thrust capabilities.

VARIABLE PITCH (GAS TURBINE ENGINE)

All turbo-prop aircraft have variable pitch propellers; normally with full feathering and reverse thrust capabilities.

Although the aerodynamics concerned is the same for piston and turboprop engines, the pitch control system for the turboprop is more complex.

AERODYNAMIC PRINCIPLES

Whether it is a basic fixed pitch propeller or a highly advanced variable pitch propeller, the aerodynamic principles that apply stay exactly the same.

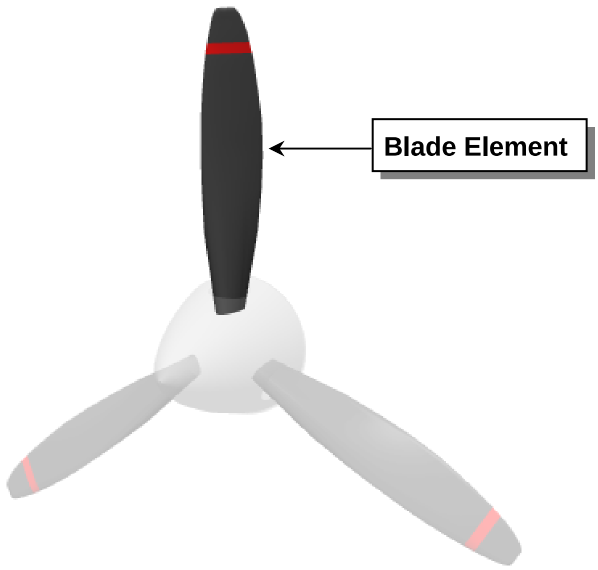
The basic aerodynamic principles pertaining to propeller theory are the following:

BLADE ELEMENT

A propeller may consist of two or more blades.

The easiest way to explain the aerodynamics of a propeller is to consider the motion of **one section (or element)** of the propeller blade.

As each part of a propeller blade has a cross-section similar to that of an aerofoil, the aerodynamics can be studied in the same terms as that of an aerofoil section.



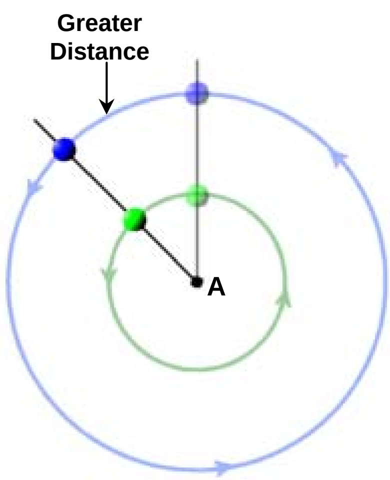
The motion of a propeller blade element describes a helical path that consists of a rotational velocity and a forward velocity.

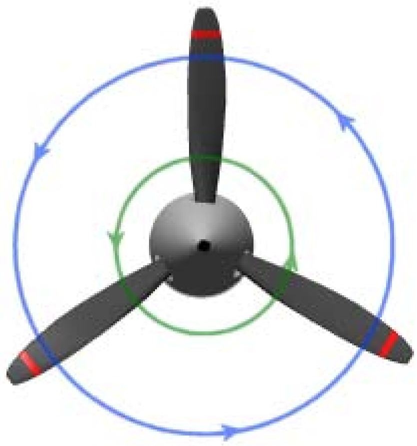
ROTATIONAL VELOCITY

The formula for the circumference of a circle is **$2\pi r$**. Therefore, as the radius of a circle increases, so will the circumference.

Consider two objects orbiting point A at the same angular velocity (rate of change of angle in degrees per sec).

The outer object will have a larger distance to cover in the same time as the inner object; therefore its velocity (rotational velocity) will be greater.





The same concept can be used when discussing propeller motion.

ROTATIONAL VELOCITY

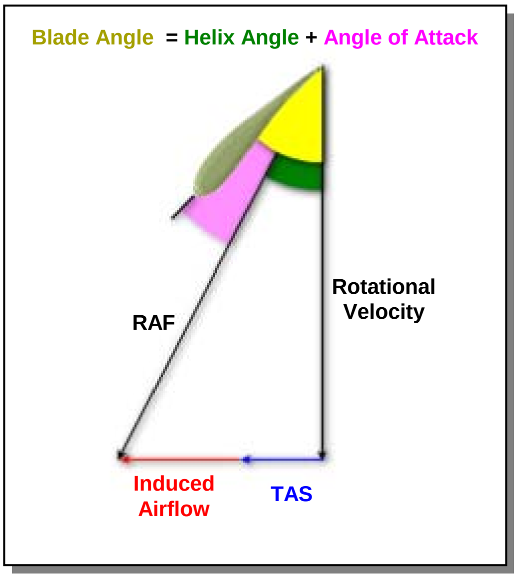
= circumference x angular velocity
= $2\pi r\omega$

The velocity of any part of the blade element will depend on the angular velocity (ω) and the radius (r) from the centre of the propeller.

It is therefore apparent that at a constant RPM, the rotational velocity of a blade element will increase as the radius (r) increases towards the propeller tips.

FORWARD VELOCITY

If an aircraft is moving forward, but the propeller remains stationary, the motion of any blade element is entirely due to the forward speed (**TAS**) of the aircraft.



When the propeller starts to turn (rotational velocity) it draws air through the propeller disc (**induced air flow**). The induced airflow is added to the TAS.

With the propeller shaft parallel to the direction of flight, the rotational velocity produces the resultant path of the blade element (RAF). The angle between the resultant path of the blade element and the rotational plane is known as the **helix angle**.

In order to produce an aerodynamic force (thrust), the blade element has to be set at a positive **angle of attack** (α) to the resultant relative airflow RAF (induced air flow + TAS).

The helix angle + angle of attack is the blade or pitch angle for that blade element.

BLADE TWIST

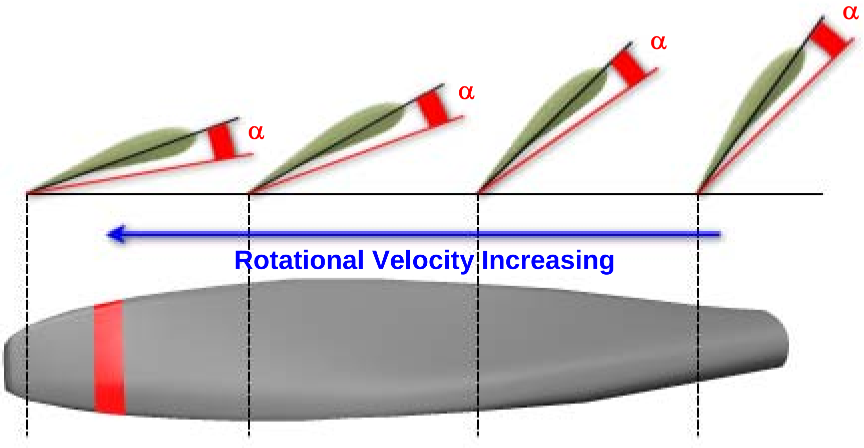
As mentioned above, rotational velocity on a propeller blade increases towards the tips. As the rotational velocity vector increases for a given TAS, helix angle decreases, hence blade angle must be reduced because:

AoA = Blade Angle – Helix Angle.

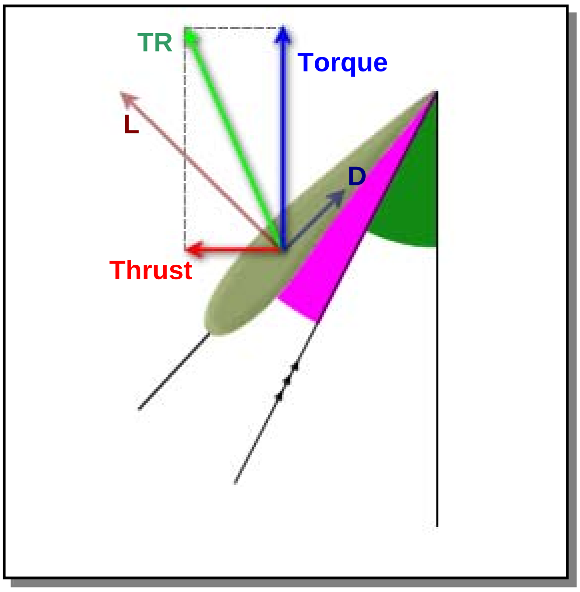
For maximum propeller efficiency, it is desirable that the angle of attack of the blade maintains a constant, efficient value throughout the span of the blade.

The blade twist can be seen in this image

For this reason blade or helical twist is found on all propellers.



FORCES ON A BLADE ELEMENT



It was stated that the aerodynamic principles that affect a propeller, are the same as that for an aerofoil.

Due to the positive angle (α) at which each blade element is set and the direction of the resultant RAF, the blade section produces **lift** and **drag** in the same way as an aerofoil.

However, with a propeller, the forces parallel and perpendicular to the RAF are not the most important.

The forces of interest are those that act along the axis of rotation (**thrust**) and at right angles to the axis of rotation (**torque**).

The propeller torque force is the resistance to motion in the plane of rotation, and just as drag must be overcome to provide lift, so the propeller torque has to be overcome to provide thrust.

PROPELLER EFFICIENCY

The efficiency of a propeller is the ratio of useful work given out by the propeller, to the work put into it by the engine.

$$\text{Propeller Efficiency} = \frac{\text{Power Output}}{\text{Power Input}}$$

The **power output** extracted from the propeller is the product of thrust x TAS.

Power input to the propeller has to overcome the rotational drag of the propeller and is the product of propeller torque x rotational velocity ($2\pi N$).

Thus, propeller efficiency can be calculated from:

$$\text{Propeller Efficiency} = \frac{\text{Thrust X TAS}}{\text{Torque x } 2\pi N}$$

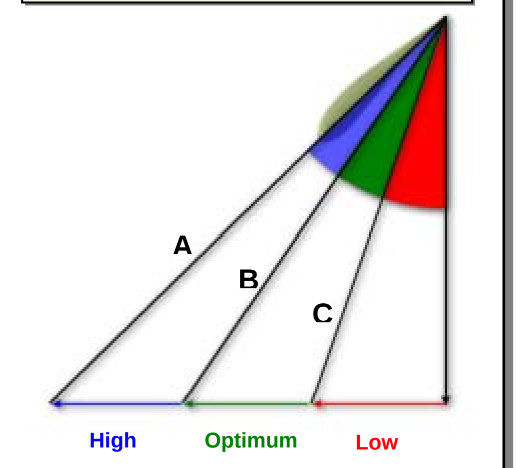
The power delivered by a propeller is measured in **thrust horsepower (thp)** while the power delivered by the engine is measured at the propeller shaft in **brake horsepower (bhp)**.

Therefore:

$$\text{Propeller Efficiency } (\eta) = \frac{\text{Thrust Horsepower}}{\text{Brake Horsepower}}$$

VARIATION OF PROPELLER EFFICIENCY WITH SPEED

The graphic shows a fixed pitch propeller at constant RPM, but at different forward speeds.



Fixed pitch propellers are not very efficient, as the angle of attack varies with changes in forward speed.

As speed increases, the angle of attack decreases and with it the amount of thrust produced. Thus, maximum efficiency on a fixed pitch propeller is achieved at only one speed for any given propeller RPM.

At some **high forward speed** (A) the angle of attack gets close to the zero lift incidence and thus thrust output is zero. Therefore propeller efficiency will also be zero.

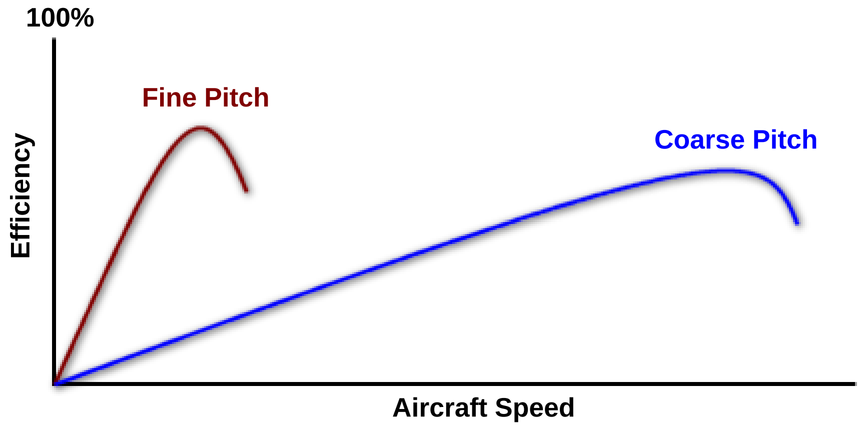
The most efficient blade angle of attack and maximum propeller efficiency is found at one speed, known as the **optimum speed** (B).

As the **speed decreases** (C), the thrust will increase due to the increase in angle of attack. As long as the blade is not stalled, thrust remains large, but efficiency is low due to the low speed.

These limitations led to the development of the **two-pitch propeller**.

With the two-pitch propeller "**fine-pitch**" was used for take-off and climbing, while the "**coarse-pitch**" was used for cruising and high-speed flight.

However, at these settings it was for all practical purposes still a fixed pitch propeller.



PROPELLER CONTROL

PISTON ENGINES

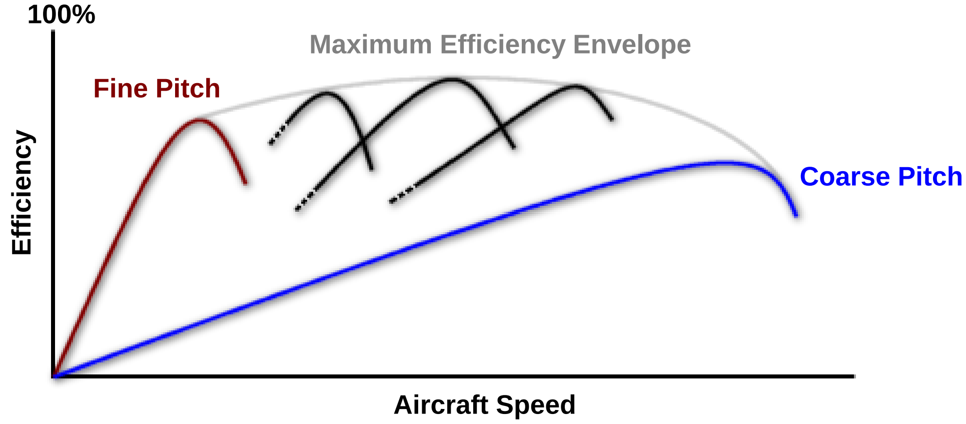
As was stated, a fixed pitch propeller achieves its maximum efficiency at only one speed. The RPM of a fixed pitch propeller depends on the power setting and aircraft speed and extreme care must be taken to prevent the engine from over speeding during a dive.

Although the two-pitch propeller was an improvement, it still was not as efficient as required and it led to the development of "**constant speed**" propellers for piston engines.

As piston engine power settings are defined by RPM and MAP (manifold air pressure), the constant speed propeller allows the pitch and thus the RPM to be selected anywhere between the fine and coarse pitch stops.

Once a RPM is selected, the engine speed is maintained by the pitch control unit (basically a governor), despite any power or airspeed changes.

The main advantage of a fully variable pitch or constant speed propeller is the overall improvement in efficiency. As can be seen on the graph below, the efficiency of a constant speed propeller matches the maximum efficiency envelope.

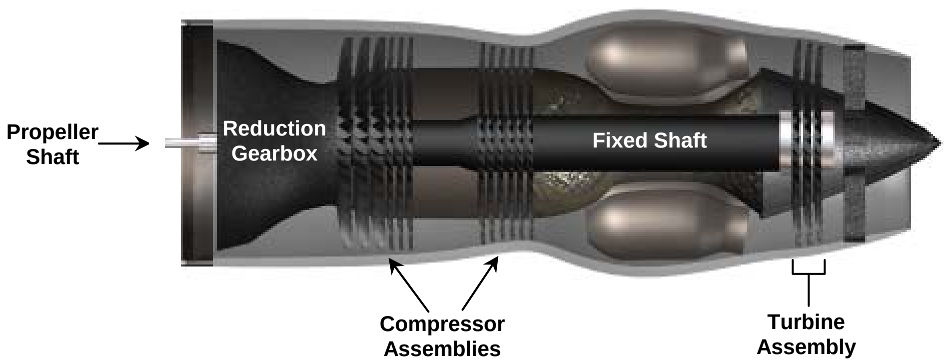


TURBINE ENGINES

There are three main types of gas turbine engines, and as the different gas turbine types have different propeller control considerations, each will be considered individually:

FIXED SHAFT TURBINE

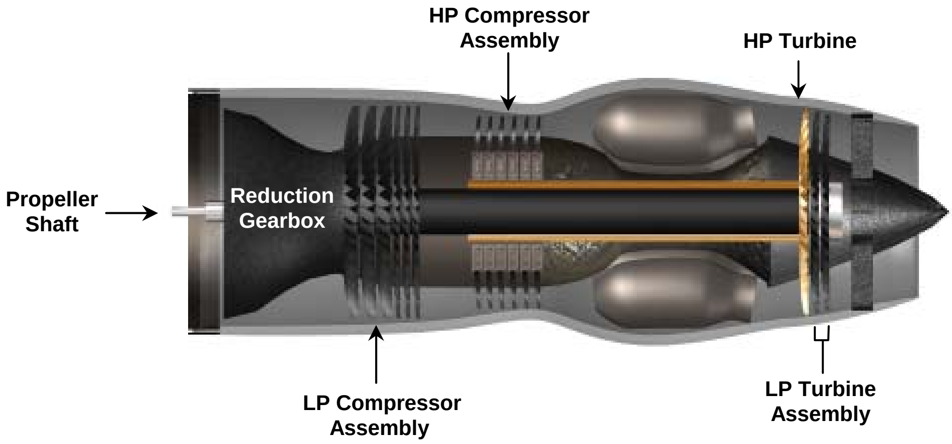
With a fixed shaft gas turbine, the propeller (through a reduction gearbox) is driven by the same shaft that carries the compressor and turbine assemblies.



The propeller RPM and fuel flow to the gas turbine must be controlled carefully and matched closely so as to avoid the risk of turbine surging, over-fuelling or flameout.

COMPOUND COMPRESSOR TURBINE

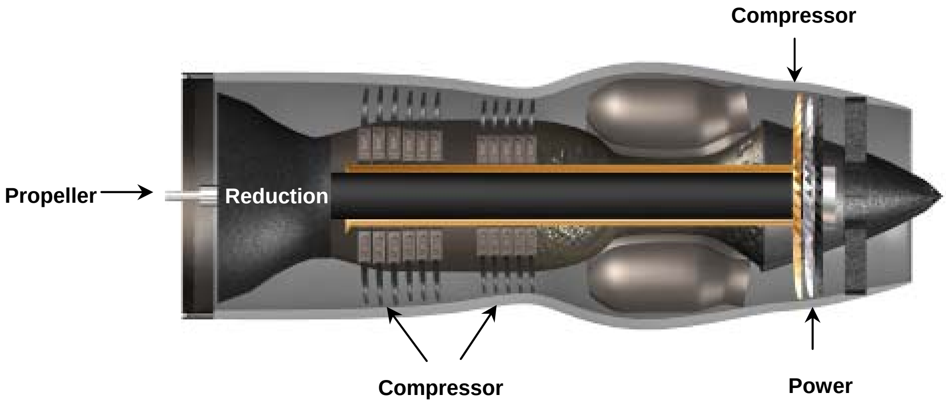
Although there are a couple of differences in layout, the compound compressor turbine may be regarded as a fixed shaft turbine and the control of the propeller is very similar.



There are two shafts (or spools); one carries the high pressure (HP) compressor and turbine assemblies and the other the low pressure (LP) compressor and turbine assemblies as well as the propeller shaft (through a reduction gearbox).

FREE TURBINE

In the case of a free turbine engine, the gas generator that comprises a shaft carrying the compressor and turbine assemblies is not mechanically connected to the propeller.



A separate turbine, driven by the high-pressure gas generated by the gas generator, drives the propeller (via a reduction gearbox).

This gives greater freedom and flexibility in propeller control as the power is controlled by the throttle and the propeller RPM by a separate pitch control unit which governs RPM to the selected RPM.

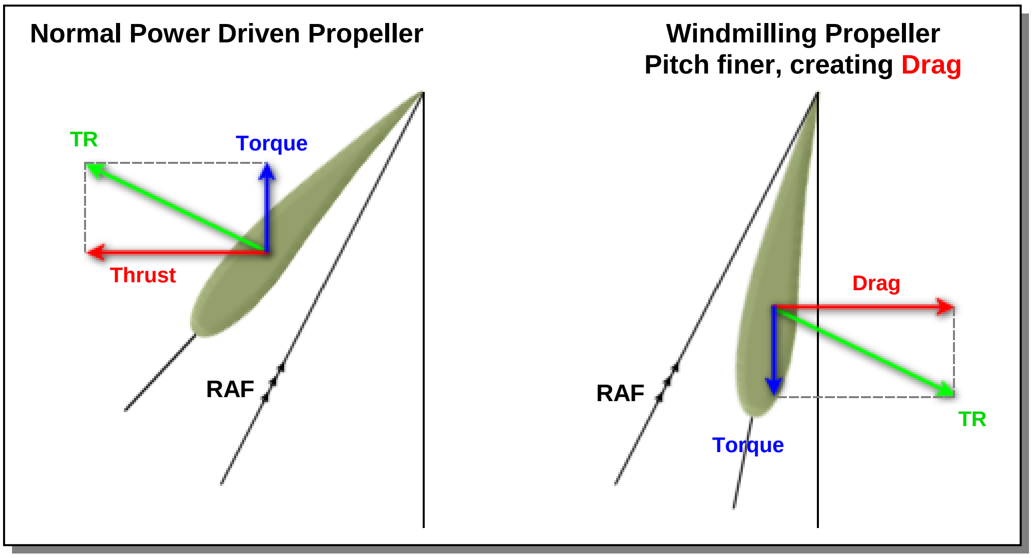
GENERAL MODES

Not only is the variable pitch propeller a vast improvement on the fixed pitch variety, but modern variable pitch propellers on both piston and turbine engine aircraft can be operated in more modes than normal flight.

WINDMILLING

During normal operation, a constant speed propeller will maintain a constant RPM and thus produce thrust for as long as there is a positive torque force applied to the propeller by the engine.

However, should the propeller suffer a loss of positive torque due to engine failure or reduction in power, the governor will still attempt to maintain the selected RPM and the pitch of the propeller will fine off.

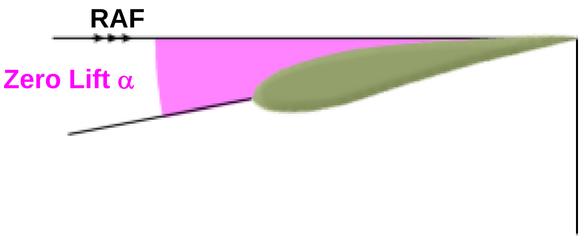


As the pitch becomes finer, the RAF will impinge on the front surface of the blade section and produce **drag** and **negative torque** that will tend to drive the engine.

A windmilling propeller is a dangerous situation to be in due to the excessive drag that is generated by the propeller.

FEATHERING

The effect of the drag of a windmilling propeller is to severely limit range, reduce performance and possibly even lead to loss of control.



Blade that has been Feathered

Also, if a damaged engine continues to turn, it may seize, or even catch fire.

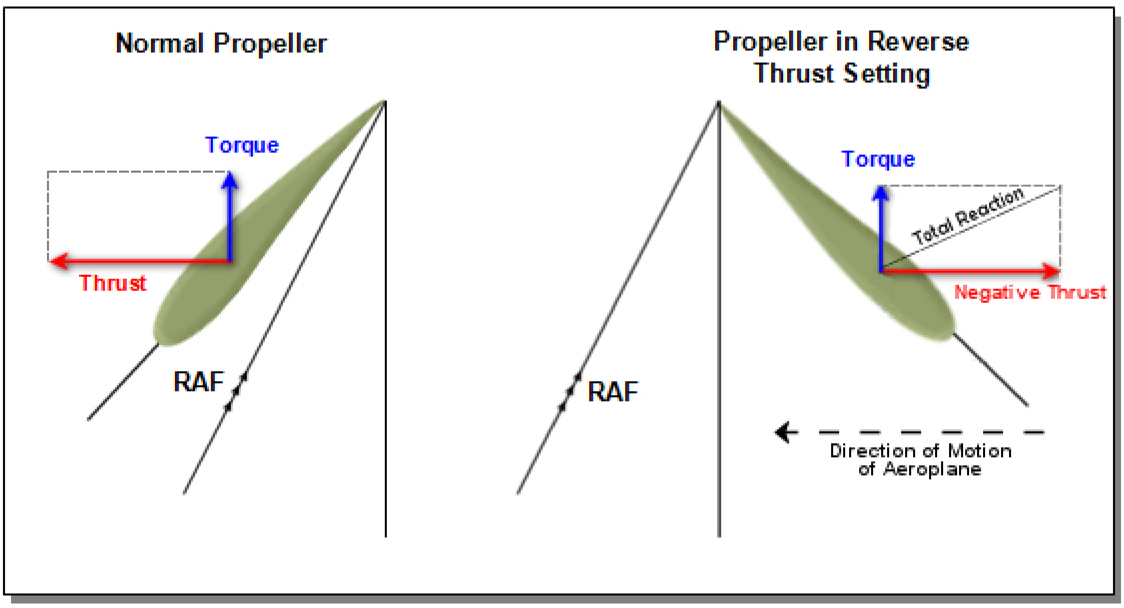
For these reasons, modern propellers on turbine-powered aircraft have a feathering capability.

The blades are turned so that the collective effect of all the blade sections produces zero torque and therefore the propeller will stop turning.

Drag is reduced to a minimum and further possible damage to the engine is prevented.

REVERSE THRUST

Most turbine-powered aircraft are also equipped with propellers with a thrust reversing capability.



Reverse thrust is obtained by turning the propeller past the fine pitch stop to about -20° and applying power. The blade is "up-side-down" and thus it produces thrust in the opposite direction.

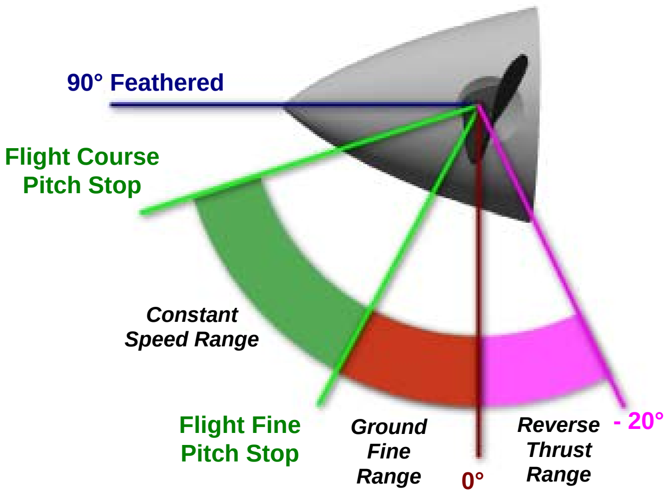
Over speed (as the propeller passes beyond the fine pitch stop) is prevented mechanically until the propeller pitch is in the braking range.

Reverse thrust is used to shorten the after landing roll and so achieve better short field performance for transport aircraft operating into unprepared or semi-prepared airstrips.

SUMMARY

Below is a graphical summary of the three modes that are available on modern variable pitch propellers.

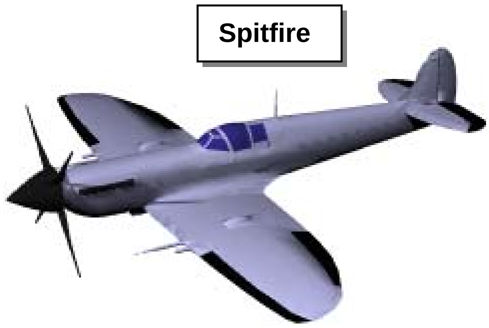
- When the propeller is **feathered**, the blade angle is 90°.
- The **constant speed range** varies from aircraft to aircraft between flight fine pitch stop and flight coarse pitch stop.
- The **ground fine range** is used for ground handling and varies between flight fine pitch stop and 0° blade angle.
- **Reverse thrust** is produced between 0° and –20° blade angle.



PROPELLER THEORY

INTRODUCTION

The Spitfire, as with most other Second World War fighter aircraft, was known to have a vicious swing on take-off, and many young and inexperienced pilots were caught out by this behaviour of the aircraft.



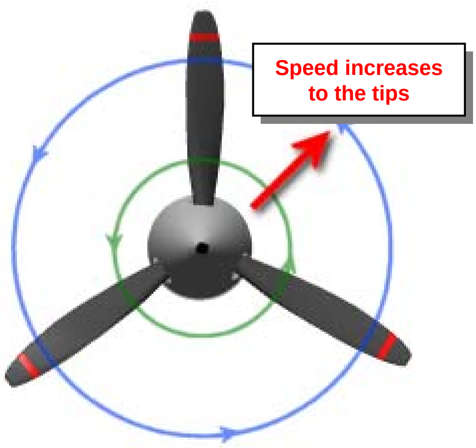
Some aircraft of World War II vintage (the Grumman F-8 Bear-Cat) could not be taken off at full power due to the immense torque generated by the propeller and engine combinations.

Propellers on different aircraft configurations such as tail wheel- and nose wheel aircraft, multi engine etc, and all produce different effects that have to be mastered in order to handle an aircraft safely.

There are also a few practical implications leading from the basic principles.

POWER ABSORPTION

Any propeller must be able to absorb the power produced by the engine and convert this power to thrust as efficiently as possible. Where engine power output (Brake Horsepower BHP) exceeds the torque produced by the propeller, the propeller will tend to "race" and both engine and propeller will become inefficient.



When matching engine and propeller, the tip velocity of a propeller is a critical factor and has to be considered.

When the propeller tips exceed the speed of sound due to too great a rotational velocity, compressibility effects increase rotational drag.

The increased rotational drag greatly reduces the efficiency of the propeller blade.

Therefore a limitation is imposed on the propeller diameter, RPM and the maximum TAS at which it can be used.

A blade with low tip speeds will reduce noise levels and propeller diameter is determined by ground clearance and distance available between the engine nacelle and fuselage.

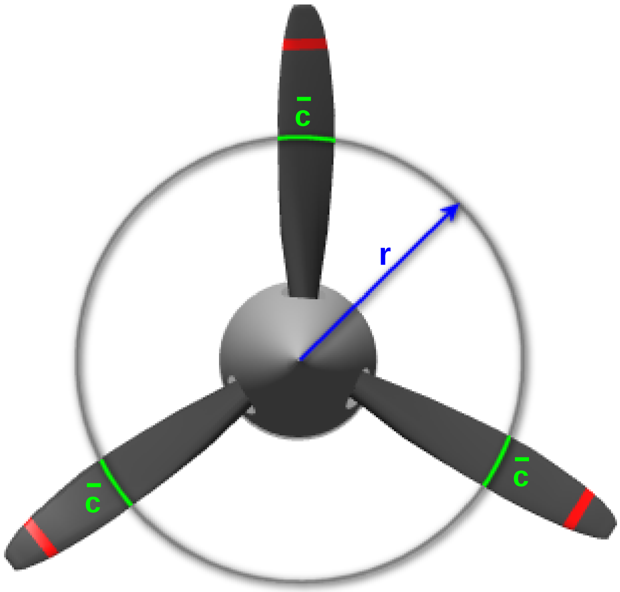
Thrust is produced by the "solid" part of the propeller. Propeller "solidity" is the ratio between that part of the propeller disc ( ) which is solid and the circumference at that radius (**r**).

Solidity at a given radius (normally 70% from the base of the blade) is given by the following formula:

Solidity = $\dfrac{\textbf{Number of Blades x Chord at Radius r}}{\textbf{Circumference at Radius r}}$

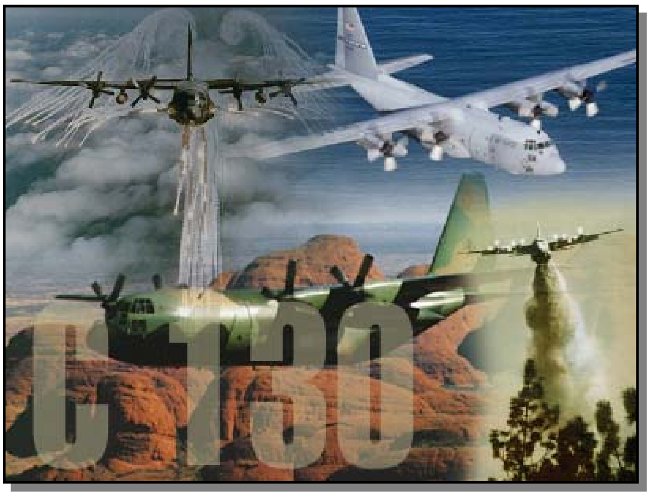
or

$$= \frac{3\bar{c}}{2\pi r}$$ *(for a 3 bladed propeller)*



The usual method that is used to absorb more power from an engine is to **increase** the solidity of a propeller. This can be achieved in two ways:

- The number of blades can be increased. Contra-rotating propellers are used on such aircraft as the **Tupolev TU-95 Bear** and Antonov An-22 Cock.



- The chord of the blades can be increased, which leads to the "paddle" blades as used on the C-130 and various other aircraft.

Note:

Although the use of paddle blades is the easier route to follow, the lower aspect ratio of the blades makes them less efficient.

TWISTING MOMENTS

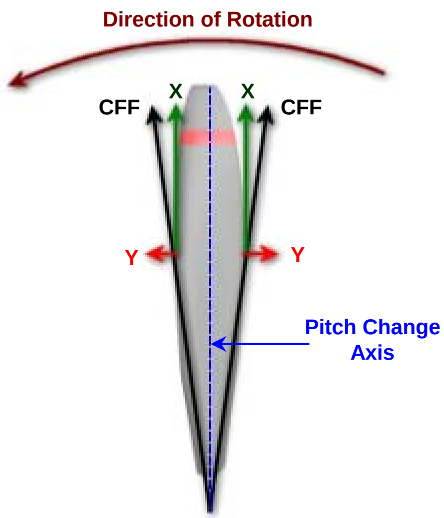
During flight considerable forces and stresses are placed on the engine, propeller and pitch changing mechanisms. The most important of these forces are:

CENTRIFUGAL TWISTING MOMENT

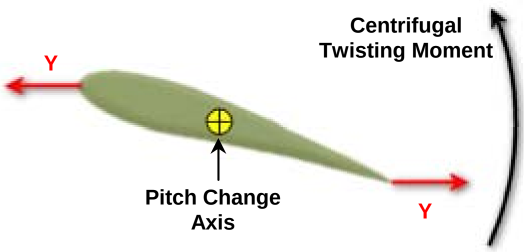
The centrifugal force (CFF) that acts on a blade can be divided into two components.

These are the **radial** (**x**) and **tangential** (**y**) components of the CFF.

The x-component produces a tensile stress at the blade root, while the y-component produces a torque moment about the pitch-change axis.



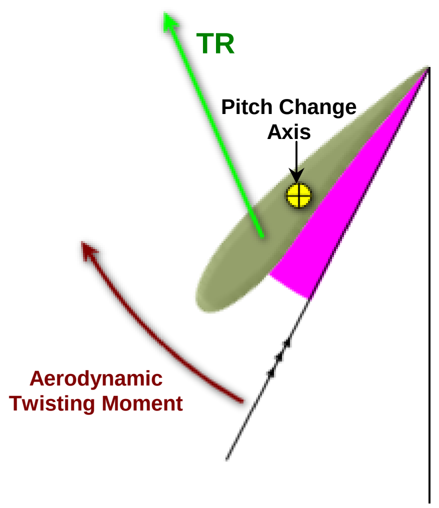
Tensile strength of a material is the resistance of that material to a force that tends to tear it apart and is normally expressed as the maximum longitudinal stress that it can withstand.



Torque produced by the CFF **y-component** causes a centrifugal twisting moment about the pitch-change axis that tends to "fine", or decrease, the pitch.

Thus, the effort required by the pitch-change mechanism is larger to increase the blade angle than it is to reduce the blade angle.

AERODYNAMIC TWISTING MOMENT



The position of the centre of pressure (TR) relative to the pitch-change axis on the blade element, will determine the size and direction of the aerodynamic twisting moment.

In the case where the TR is ahead of the pitch-change axis (as is normally the case), the aerodynamic twisting moment produced, will increase the torque on the blade.

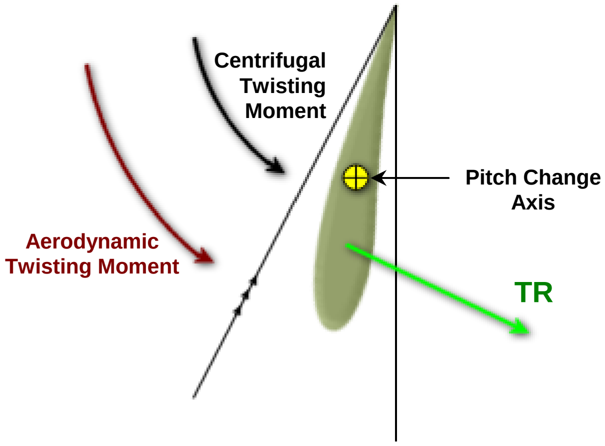
This aerodynamic twisting moment will tend to increase the pitch angle of the blade and in so doing, partially offset the centrifugal twisting moment.

WINDMILLING TWISTING MOMENT

Due to the fact that the RAF strikes the front of a windmilling propeller, the aerodynamic twisting moment is reversed.

Now both the **centrifugal**- and **aerodynamic** twisting moments act in the same direction.

The combined effect could be a critical factor when it becomes necessary to operate the pitch-change mechanism successfully.



A dangerous situation could develop if the combined twisting moments prevent the propeller from being feathered in an emergency situation.

Note:
In a twin-engine aircraft with marginal single engine performance, it is imperative that the additional, excessive drag produced by a windmilling propeller be reduced to minimum as quickly as possible so as to maintain a safe operating height and control of the aircraft.

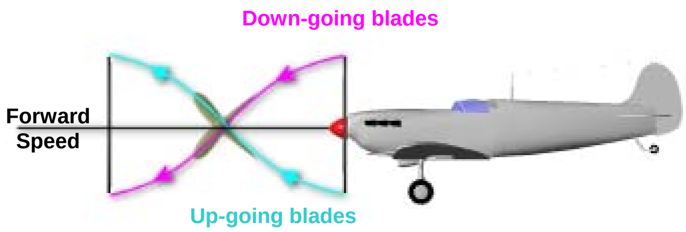
CAUSES OF SWING ON TAKE-OFF

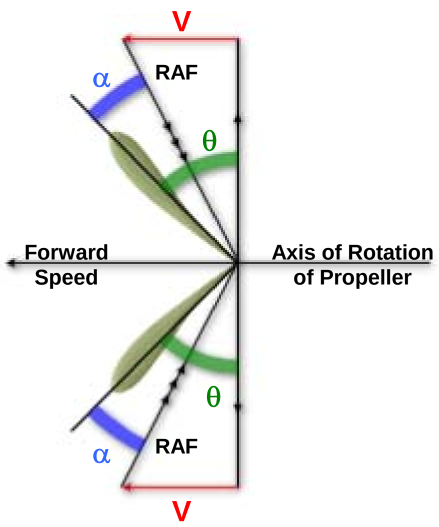
Most aircraft with tail wheel type undercarriage (tail draggers) have the tendency to swing to one or the other side during take-off. This swing is caused by various factors.

ASYMMETRIC BLADE EFFECT

Consider an aircraft in a level attitude which is maintaining a constant propeller RPM.

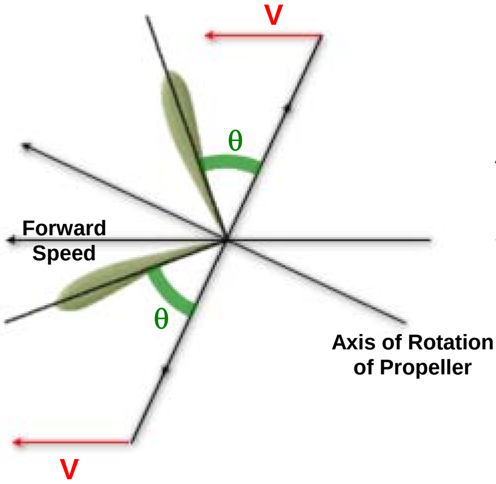
In a level attitude, the axis of rotation of the propeller and the direction of movement of the aircraft is the same.





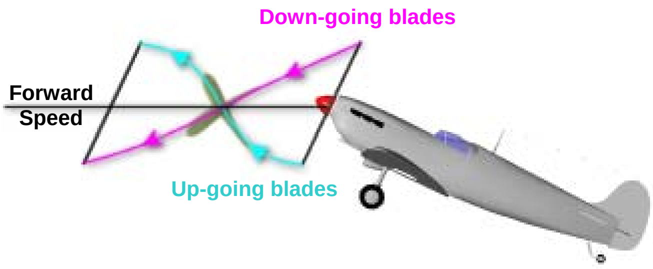
At a constant RPM, the up- and down-going blades both have the same angle of attack (α) and the **RAF** on both propeller sections is equal. Thus, both the up- and down-going blades will travel the same distance per unit time.

Now consider the same aircraft still at a constant RPM, but with a high nose attitude.



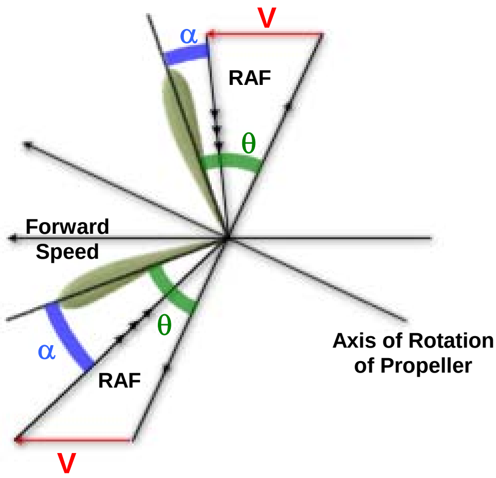
Although the axis of rotation is inclined due to the high nose attitude, the direction of movement remains the same, and V (TAS) and rotational velocity remain at constant values.

Due to the axis of rotation being inclined, the down-going blade has to cover a greater distance per unit time than the up-going blade and thus the down-going blade has a greater velocity than the up-going blade.



Due to the higher velocity of the down-going blade, the resultant RAF will be greater than on the up-going blade.

Although the **blade angles (θ)** remain the same on both up- and down-going blades, the **angle of attack (α)** increases on the down-going blade, while decreasing on the up-going blade due to the inclination of the propeller axis of rotation.



The down-going blade produces more thrust because:

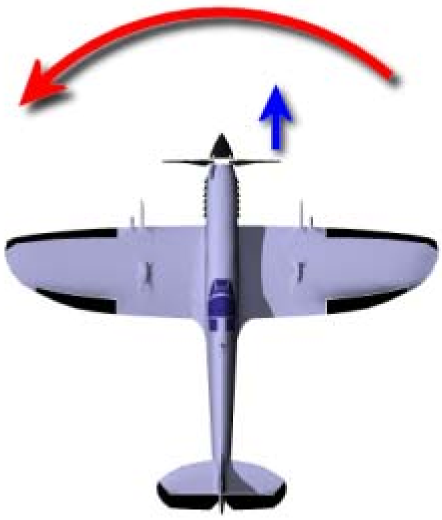
- It has a greater α than the up-going blade
- As the distance travelled by the down-going blade is greater than the up-going blade, it produces more thrust for the same α by virtue of the greater resultant RAF (***indicated by a longer RAF vector***).

The effect of the down-going blade producing more thrust when the propeller disc is inclined is known as the <u>asymmetric blade effect</u>.

When an inclined propeller (such as on a tail dragger during take-off) is rotating clockwise as seen from the cockpit, the right-hand half of the propeller disc produces more thrust and thus produces a yawing moment to the left due to the asymmetric blade effect.

When the direction of rotation of the propeller is changed from clockwise to anti-clockwise, all yawing moments will be reversed.

Asymmetric Blade Effect



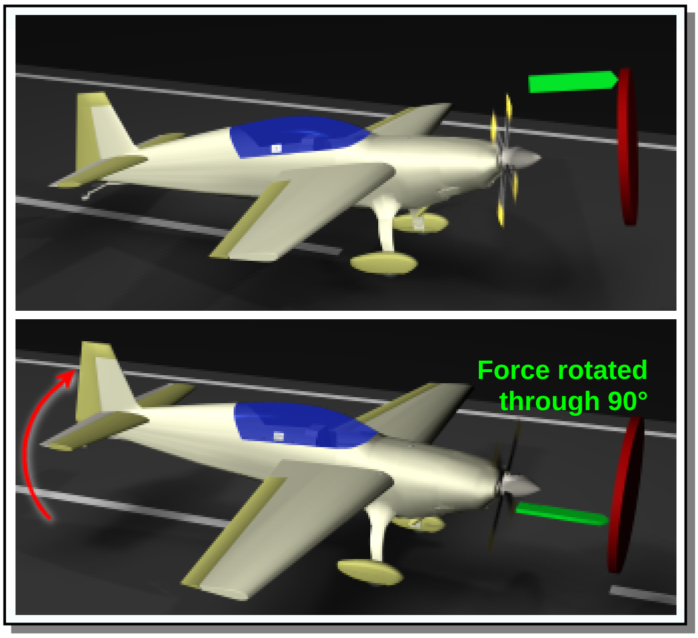
GYROSCOPIC EFFECT

Due to the speed at which a propeller turns, as well as its weight, it forms a very rigid gyro. Therefore a turning propeller possesses the same properties as a gyro, namely - **rigidity** and **precession**.

Consider a tail dragger aircraft with its propeller rotating clockwise as seen from the cockpit, during take-off.

When the tail is raised during take-off, a force is applied at the top of the propeller disc as the disc is rotated.

With the spinning propeller possessing the same properties as a gyro, that force is precessed through 90° in the direction of rotation.

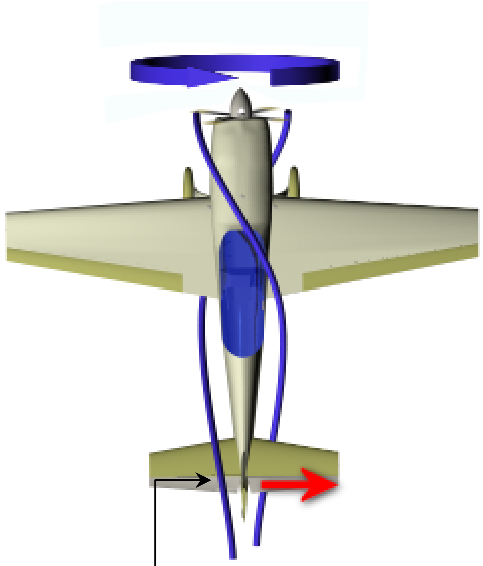


Due to precession, the force acts at the right side of the propeller disc and it now produces a gyroscopic yawing moment to the left.

Take note

- **The force only acts for as long as it takes to rotate the tail to the level attitude.**
- **If the direction of rotation of the propeller is changed from clockwise to anti-clockwise, the yawing moment will be reversed.**

SLIPSTREAM EFFECT



The AOA on the fin is increased, creating an aerodynamic force to the right.

Consider an aircraft with the propeller rotating clockwise as seen from the cockpit.

The propeller will impart a rotation to the slipstream behind it in the same direction as it is rotating.

This rotation of the slipstream produces an asymmetric flow over the fin and rudder.

The asymmetric flow produces an aerodynamic force to the right that in turn causes the aircraft to yaw to the left.

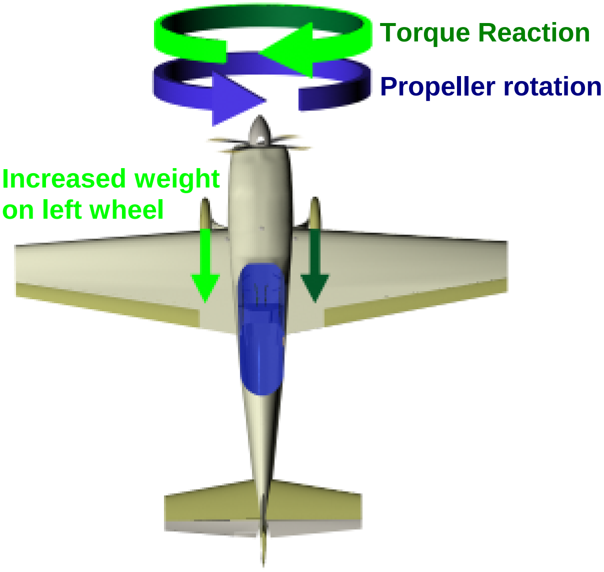
If the direction of rotation of the propeller is anti-clockwise, the aerodynamic force will be produced in the opposite direction, causing the aircraft to yaw to the right.

TORQUE EFFECT

If a propeller rotates clockwise (<u>to the right</u>) as seen from the cockpit, the torque reaction will tend to rotate the aircraft in the opposite direction (<u>to the left</u>). (***For each action there is an equal and opposite reaction – Newton 3***).

As the aircraft is still on the ground, the wheels prevent the rolling motion and the torque is translated into additional apparent weight supported by the left wheel.

The increased apparent weight increases the rolling resistance of the left wheel and consequently the aircraft will tend to swing to the left until the wings take the weight off the wheels.



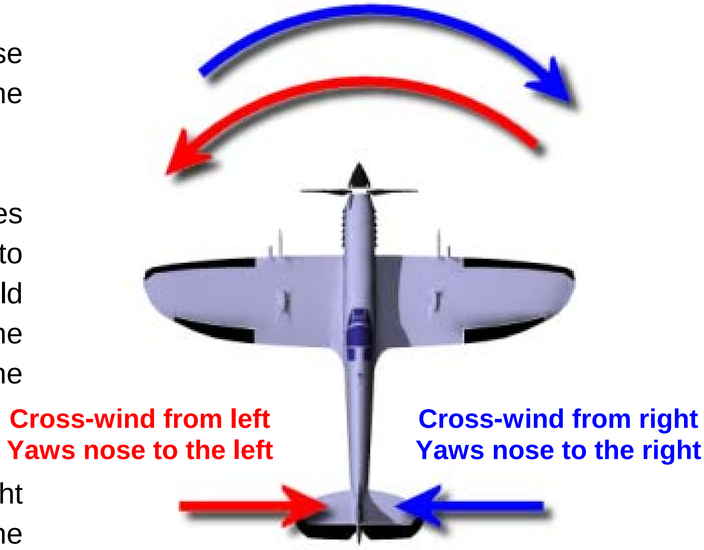
With the direction of rotation reversed, the swing due to the torque effect is in the opposite direction.

WEATHERCOCK EFFECT

The swing produced during take-off is not purely propeller generated, but can also be a result of crosswind.

A crosswind from the left will cause the nose of the aircraft to yaw to the left, due to the weathercock effect on the tailplane.

With an aircraft where the propeller rotates clockwise, all the effects produce a swing to the left. Thus a crosswind from the left could aggravate the swing to the point where the pilot loses control and the aircraft departs the runway.



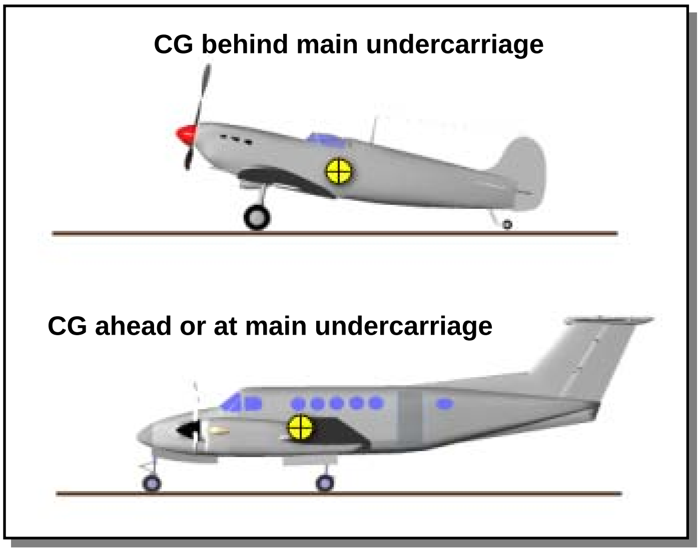
On the other hand, a crosswind from the right could negate all the other effects and the aircraft would have a straight take-off run.

NOSE-WHEEL AIRCRAFT

Not all aircraft have tail-wheel undercarriage.

As a matter of fact, with a few exceptions, modern aircraft are all equipped with a nose-wheel undercarriage.

Tail-wheel aircraft are directionally unstable due to the CG being situated well aft of the main wheels. For this reason tail-wheel aircraft exhibit divergent tendencies during ground manoeuvring.

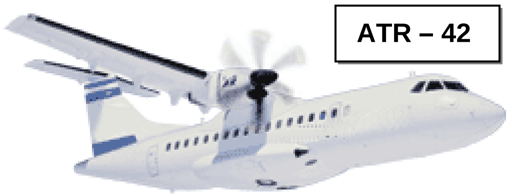


However, as the CG of a nose-wheel aircraft is normally situated ahead of or at the main wheels, these aircraft possess inherent directional stability while manoeuvring on the ground.

Also, as nose-wheel aircraft are virtually in the flying attitude during take-off, asymmetric blade- and gyroscopic effects can be ignored and although the aircraft is still subject to the torque-, slipstream- and weathercock effects, the swing is more easily controlled.

FUTURE DEVELOPMENTS

The efficiency of advanced propellers has been proven by NASA and is being used on aircraft such as the ATR-series, Dornier 328 and DHC Dash-8.



ATR – 42

The additional efficiency gained from using advanced propellers, can be used to produce more thrust from a given engine or by increasing fuel economy by utilizing a smaller engine with lower fuel consumption.

ATP's (Advanced TurboProps) have an added advantage in that they are extremely quiet and therefore reduce noise levels at and around airports.

Example of an Unducted Fan (UDF)

Future developments point to an advanced propeller with multiple blades of thin, transonic aerofoil section, driven by a gas-turbine at high sub-sonic speeds of up to Mach 0.8 and at cruising altitudes of over 30 000 ft.

Such propellers, known as Unducted Fans (UDF) or Ultra-High Bypass (UHB) fans, are already being evaluated by NASA and various large aircraft manufacturers and test-flown on aircraft such as the MD-80 of the McDonnel-Douglas Corporation.