Groundschool – Theory of Flight

Engine and propeller performance

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Module content

Engine power is the product of torque and engine speed. Two-stroke engines favour engine speed to produce the power and are very inefficient at other than high rpm; four-stroke engines use lower rpm and higher torque. The efficiency of normally aspirated engines decreases with altitude — but turbocharging helps considerably.

The propeller converts engine power into an aerodynamic force. The portion of the force acting forward is the thrust power, and the portion acting in the plane of rotation is the propeller torque. In unaccelerated level flight, the propeller torque balances the engine torque while thrust balances the aircraft's aerodynamic drag. The thrust conversion efficiency depends on the propeller configuration and aircraft speed. The simple fixed-pitch configuration is inefficient at most speeds. The variable-pitch, constant-speed propeller is reasonably efficient at most speeds.

5.1 Engine power output

Engine power equals the product of force and speed. **Torque** is the rotational force acting about the engine crankshaft multiplied by the moment arm; i.e. it is the product of the firing stroke in the cylinder and the radius of the crank to which the connecting rod is attached. The bigger the cylinder the bigger the rotational force — the 'bang'. Engine speed is measured in crankshaft revolutions per minute [rpm].

In the 'Manoeuvring forces' module we discussed the power required for various flight conditions, and looked at power required/power available curves and the effect of altitude on power output. It may be appropriate to review section 1.7 of that module.

Normally aspirated aero engines

The maximum power that can be developed, in the cylinders of a particular piston engine, increases or decreases directly with the density of the air in the intake manifold, and air density decreases as altitude increases — or temperature increases. See the atmospheric density and the International Standard Atmosphere sections in the 'Airspeed and the properties of air' module. Thus, the full throttle power output of a **normally aspirated** engine — one that relies solely on the ambient atmospheric density — decreases as operating altitude increases. The diagram in section 1.7 shows how maximum brake horse-power [bhp], delivered at full throttle in a normally aspirated engine, decreases with altitude. A 100 hp engine operating at 65% power will be delivering 65 hp.

Power produced is proportional to the air density at the intake manifold, the cylinder displacement and compression ratio, the number of cylinders, and the rpm. Of those items, only the air density at the intake manifold and the engine rpm alter, or can be altered, during flight. *(With a normally aspirated engine and a propeller whose pitch is not variable in flight, the throttle controls manifold pressure, which then determines rpm.)* A traditional four-stroke light aircraft engine, such as the Lycoming O-235, has an individual cylinder displacement of 950 cc, a compression ratio of 7:1 and a maximum design speed of 2600 rpm, at which its rated 110 bhp is produced — in sea-level ISA conditions. The Rotax 912, the most common lightweight four-cylinder aero-engine, utilises an individual cylinder displacement of only 300 cc, a compression ratio of 9:1, but doubles the maximum design speed to 5500 rpm to achieve its rated 100 bhp. The lightweight Jabiru 2200 utilises an individual cylinder displacement of 550 cc, a compression ratio around 8:1 and a maximum design speed of 3300 rpm to achieve its rated 80 hp.

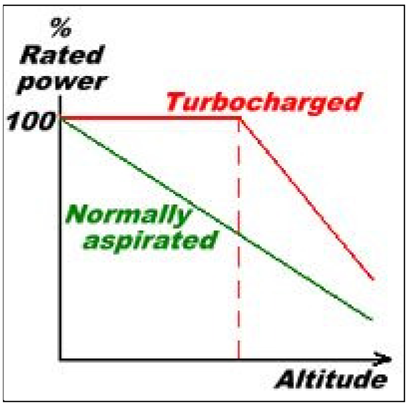
The three engines mentioned are all horizontally opposed, four-stroke and four-cylinder; a popular configuration providing a fully balanced engine that doesn't require crankshaft balance weights. Engines are often described in terms of 'total capacity' (cylinder displacement by number of cylinders) in litres or cubic centimetres. Thus, the Lycoming O-235 is 3.8 litres or 3800 cc (235 cubic inches), the Rotax 912 is 1.2 litres and the Jabiru 2200 is 2.2 litres. Most engines used in ultralights tend to be around 30% lighter (in terms of weight per rated hp) than the ubiquitous Lycoming and Continental piston engines used in general aviation aircraft. Thus, they are cheaper to manufacture but less robust, with a consequent shorter time between overhaul [TBO].

Although aero-engines can quite happily operate continually at their rated power, doing so is not good practice. It is uneconomical in terms of fuel efficiency, but — more importantly — it may shorten engine life, if engine operating temperatures and pressures are exceeded. Normally the maximum — and optimum — power setting for continuous cruise operation is 75% of rated power.

Turbocharging

The volumetric efficiency (i.e. the cylinder-filling capability) of an engine can be improved by increasing the density of the fuel/air **charge** delivered to the cylinders by compressing the air in the atmospheric intake manifold. This process is **supercharging** and develops more torque at all engine speeds. The compressor is usually a lightweight centrifugal impeller driven by a gas turbine that utilises the otherwise wasted energy of the engine exhaust gases. Such a system is a turbine-powered supercharger, usually described as a **turbocharger**. An oilpressure-driven butterfly valve or **waste gate** is incorporated within the exhaust manifold system, automatically adjusting — according to the pressure within the intake manifold — to allow all, or a portion, of the exhaust gases to bypass the turbine; thus continually maintaining the system within the designed operating limits. There is a slight penalty in that turbocharging also increases the temperature of the charge. This consequently decreases the achievable density and possibly leads to detonation, unless a charge cooling device — an **intercooler** — is incorporated between the compressor and the cylinders.

For some information on mechanically powered supercharging, read this magazine article.



Turbocharging may be used to increase the sea-level rated power of the engine, but the use of that full throttle power at low altitudes would normally be limited to short periods because of engine temperature limitations. The big advantage is the increase in power available at altitude. The diagram plots the power achieved (percentage of rated power) at full throttle, in ISA standard conditions, for a normally aspirated engine and the turbocharged version. The turbocharged engine can maintain its rated power from sea-level up to the 'critical altitude', probably around 6000 or 7000 feet, after which it will decrease. The waste gate would probably be fully open at sea-level and then start closing as altitude increases — so that it would be fully closed at, and above, the critical altitude.

Turbocharging raises the service ceiling of the aircraft. The **service ceiling** is the ISA altitude at which the aircraft's best rate of climb (from an extended climb starting at MTOW and unassisted by any atmospheric phenomena) drops below 100 feet per minute — regarded as the minimum useful climb rate. This should be the aircraft's ceiling quoted by the manufacturer.

The Rotax 914 series 115 hp turbocharged engines are often regarded as just being suitable for ultralight aircraft. However, those engines power the Predator RQ1/MQ1, unmanned aerial reconnaissance and surveillance vehicles, used so successfully in the Afghanistan and Iraq campaigns of recent years. The Predators have a maximum take-off weight around 1000 kg, cruise around 90 knots, normal mission duration around 20 hours — but could operate for 40 hours — and service ceiling of 25 000 feet. They often carried two 50 kg Hellfire missiles for attacking acquired targets — they also need 5000 feet of paved runway for take-off.

Two-stroke aero engines

The lower power (say, up to 65 hp) engines used in ultralight aircraft are usually two-stroke engines, although the half-VW four-stroke auto engine conversions are around 40 hp. Two-strokes don't have very good volumetric efficiency, and the engine is efficient only in a narrow rpm and throttle opening range occurring at very high rpm. In fact, ultralight two-strokes tend to run very roughly at speeds below 2500 rpm. The three most common two-strokes are two-cylinder models with individual cylinder displacements around 250 cc; they achieve their rated power at 6800 rpm. Power drops off very quickly as rpm is reduced below that figure. Gearing or belt reduction is used to improve the torque delivered to the propeller shaft while also reducing the rpm to something more suitable for the propeller. The torque increases because of the larger rotational radius of the driven gear.

The big advantage with two-stroke engines is their mechanical simplicity, and consequent weight and cost saving, because they lack the camshaft and associated valve train of the four-strokes. Some very small (15 hp) two-strokes are used to power self-launching powered hang-gliders. Between 1999 and 2003, there were 98 engine failures reported to RA-Aus; 39 were two-stroke engines and 59 were four-stroke. It is estimated at that time about 65% of the ultralight fleet, of some 1800–2000 aircraft, were equipped with two-strokes. It would appear during that period the two-strokes were more reliable than the lightweight four-stroke aero-engines, though the development of lightweight four-strokes was then not as far along the learning curve as two-stroke development.

5.2 Propeller power output

An aircraft engine supplies energy, in the form of rotational power, to the propeller shaft. The propeller converts the rotational power to thrust power, either pulling the aircraft along behind it (a tractor installation) or pushing the aircraft in front of it (a pusher installation). The propeller accelerates a tube of air, with much the same diameter as the propeller disc; i.e. it adds momentum to the tube of air and the reaction force propels the aircraft forward. The velocity of this accelerated airstream (the *slipstream*) has both rotational and rearward components. Momentum = mass × velocity, so if the mass of air passing through per second is increased by increasing the diameter of the propeller, the rearward velocity imparted can be decreased but still produce the same rearward or axial momentum. The rate at which axial momentum is imparted to the air equates with thrust. **Propeller efficiency** is the ratio of the thrust power (thrust × aircraft forward speed) output to the engine power input.

The work done (the energy expended) by the propeller is the kinetic energy imparted to the slipstream = $\frac{1}{2}mv^2$ joules (if mass is in kilograms and v in metres per second), so less energy is expended if the mass is increased and the velocity decreased.

Using a simplified static thrust example, if m = 10 kg and v = 100 m/s, then the momentum is 1000 kg·m/s and energy expended is $\frac{1}{2} \times 10 \times 100^2$ = 50 kJ. But if the values for m and v are interchanged (i.e. m = 100 kg and v = 10 m/s) the momentum will still be the same but the energy expended will be decreased substantially; i.e. $\frac{1}{2} \times 100 \times 10^2$ = 5 kJ.

Thus, the most efficient system is to utilise the greatest propeller diameter possible — limited by:

- the stress effects on the engine (the gyroscopic moments increase exponentially with diameter; see below)
- ground clearance requirements in worst conditions (e.g. heavy landing and deflated tyre)
- propeller blade strength
- blade tip speed. *When a propeller is rotating, the speed at any point on a blade is the product of the rpm and the distance of that point from the hub, and thus the speed at the propeller tip is the greatest. Compressibility constraints dictate that the speed at the blade tips should not exceed about Mach 0.85 — 560 knots or 290 m/s at sea-level. But significant compressibility effects become evident at 250 m/s and, if the propeller is close to the pilot, the noise may be extremely uncomfortable. So, for comfort, tip speed is usually in the range 200–240 m/s.*

For light aircraft engine/propeller systems, it is usual to restrict propeller speed to less than 3500 rpm; so, the high rpm engines must incorporate a gear-driven or belt-driven propeller speed reduction unit [PSRU] between the crankshaft and the propeller shaft. The rotational speed of the fixed-pitch propeller depends on the pitch of the blades, the power supplied to the propeller and the aircraft velocity.

Propeller blade area is an important consideration in propeller design and choice. Blade aspect ratio is usually maintained around 6–8; so, with a limited propeller diameter, blade area can only be increased by increasing the number of blades.

Matching engine and propeller

Propellers must be carefully matched with the characteristics of the airframe, engine and reduction gear to which they are mated. The engine must be neither underloaded nor overloaded. At best, a mismatch could make the engine and aircraft incapable of delivering its designed performance, or create the situation where the engine cannot be opened up to full throttle because the lack of load (see the following paragraph) would take the rpm beyond the red-line limit, or it could result in crankshaft or crankcase fracture. At worst, a mismatch could lead to torsional vibration or propeller blade destruction induced by centrifugal force. This can readily cause the engine to dismount from the airframe and lead to consequent total loss of the aircraft. When discussing the power required curve it was noted that power required is proportional to aircraft velocity cubed. Similarly, the power delivered by a propeller varies in accordance with rpm cubed (if everything else is kept constant). Thus, the load on the propeller may be substantially increased just with a relatively minor further increase in rpm when operating at high rpm, which can lead to loss of the blades. Note that centrifugal forces on the blades change in accordance with the rpm squared.

Note: The load on the engine is the propeller torque. When the aircraft is stationary, with the engine throttle wide open, the propeller torque and the static thrust generated (i.e. the efficiency of the engine and the propeller combination) depend on the propeller pitch. If the pitch is zero or slightly negative, the static thrust will be zero and the propeller torque will be very low so that the engine will race — overspeed — and lose power because of inefficient cylinder *charging, etc.*

On the other hand, if the pilot is able to set the prop to a more negative pitch, then reverse thrust will be generated together with sufficient torque to maintain constant engine rpm and the aircraft will move backward.

If the pitch is 'fine' (low aoa), the propeller will generate near maximum static thrust and sufficient torque to maintain high engine rpm, thus delivering ample power to the propeller shaft. This is the ideal situation to get the aircraft rolling for take-off and climb-out.

If the pitch is very 'coarse' (high aoa), then static thrust is low but propeller torque is very high, which will slow the engine. This is the worst situation for take-off — the aircraft will move forward sluggishly and, hopefully, never reach take-off speed. For an interesting article on ground testing of aircraft engines for power output, read "Testing one, two three" in the July-August 2002 issue of 'Flight Safety Australia' *magazine.*

When an aircraft with a fixed-pitch propeller is flying the back of the power curve (i.e. an increasing thrust power output is needed as the airspeed decreases), the propeller efficiency will decrease as airspeed decreases, while the increasing propeller torque will be slowing the engine power. Thus, it may be difficult to arrest any sink that develops at low speeds — as might be experienced on the approach to a short-field landing.

However, even with an apparently well-matched engine/propeller combination, there may be a certain rpm range (or ranges) where the frequency of a particular engine vibration resonates, with some natural frequency of the propeller, to produce an intrusive vibration and a potentially damaging stress cycle. In such aircraft, that rpm range or ranges is (or should be) indicated as a yellow, perhaps red, arc on the face of the engine tachometer. Rpm settings within those ranges should not be used.

Any gyroscopic moment induced depends on the rate of change in aircraft pitch or yaw, and the rotational speed and moment of inertia of the propeller. Its mass moment of inertia depends on propeller mass and diameter. The gyroscopic loads are transferred to the airframe via the engine crankshaft, crankcase and mountings. Under some conditions, gyroscopic loads may lead to crankshaft/crankcase failures. See 'The Fox story'.

The failure conditions usually identified are the use of a propeller of excessive diameter (the moment of inertia increases exponentially with diameter) possibly combined with an excessive 'overhung' moment — the distance from the propeller cg to the engine. Excessive gyroscopic loads may also be placed on the crankshaft/crankcase by using brake, rudder and a burst of throttle to swing an aircraft rapidly when taxiing.

The flight conditions that follow propeller blade failure cannot be simulated in training, but an extreme out-of-balance condition (loss of one blade for example) can very quickly shake the engine from its mountings.

5.3 Propeller types

The following is a copy of a document authored by Marcus Graney and published on the web site of the New Zealand manufacturer of Airmaster propellers. I have added the notes presented in italic. ... JB

The most common type of propeller in sport aviation is the fixed-pitch propeller. Although cheap, this is one of the crudest propulsion devices you could use, and has been superseded by a variety of more advanced options, now readily available on the market. But, how do you know how each type of propeller operates and what advantages the different types offer? How are you going to choose between the different types available for your aircraft, especially considering that a more capable propeller is also more expensive?

There are four common families of propeller, which I will introduce to you. They are fixed-pitch, ground-adjustable, inflight-adjustable and constant-speed. The last two are both examples of **variable-pitch** propellers.

In order to appreciate the advantages which are characteristic of the different families of propeller, we must first consider the most fundamental characteristic of a propeller — the pitch. Pitch is important, as it is the manner in which pitch is controlled that allows us to differentiate between one family of propeller and another.

A useful analogy when considering the affect of pitch is that of an automobile gearbox. By comparing a propeller's pitch to a gear ratio, and considering the function of a gearbox, we will gain an appreciation of the different families of propellers.

What is pitch?

Propeller theory includes a variety of concepts that may at times be called pitch. Pitch can refer to the blade angle with respect to a flat plane, the distance that a propeller will advance through the air for each rotation or the amount of "bite" that the blade has on the air. Essentially these concepts all describe the same thing. To use our automobile analogy, pitch is like the gear ratio of the gearbox. The important thing to note with pitch, is that it is available in a wide variety of degrees, or 'amounts', much like different gear ratios. To demonstrate, consider the following examples:

- A fine pitch propeller has a low blade angle, will try to move forward a small distance through the air with each rotation, and will take a 'small' bite of the air. It requires relatively low power to rotate, allowing high propeller speed to be developed, but achieving only limited airspeed. This is like having a low gear in your automobile.

- A coarse pitch propeller has a high blade angle, will try to advance a long distance through the air with each rotation, and will take a big 'bite' of the air. It requires greater power to rotate, limiting the propeller speed that can be developed, but achieving high airspeeds. This is like having a high gear in your automobile.

Pitch and the different families of propellers

As we saw above, pitch is a key element in the description of propellers (along with other factors such as diameter and blade area). When considering the four families of propellers it is useful to start with the simple fixed-pitch propeller, and look at the enhancements in pitch control that are gained as we progress through each family to the most advanced, the constant-speed propeller.

Fixed-pitch propeller

With a fixed-pitch propeller, the pitch of the propeller is fixed from manufacture. The performance of your aircraft is determined on the day your propeller is fitted, and is going to be limited within the constraints of the propeller. An analogy with an automobile is as though you had only one gear. Often when choosing a fixed-pitch propeller for your aircraft, manufacturers give you a choice of either a climb or a cruise prop. A climb propeller has a relatively fine pitch and a cruise propeller has a relatively coarse pitch. This is like a car manufacturer giving you a choice of a low or a high gear. Either you will be really slow off the mark, or your engine is going to have to be red-lined to get anywhere at a reasonable speed.

Ground-adjustable propeller

Many propellers manufactured and sold for ultralight and experimental aircraft are ground-adjustable. These propellers have the advantage of being able to have their pitch set before each flight if required, taking into account the type of flying you intend to do. More usually however they are used as a low cost way to try out various pitches and settle on the propeller pitch that best suits your aircraft and your style of flying. This can be compared to having a gearbox in your car that you can only change before you set out on your journey.

Variable-pitch propeller

With a variable-pitch propeller, you really have choices. To use the automobile analogy again, your car now has a real gearbox that you can change gear with on the go. (I hope that your car can do this at least!) In addition, rather than being limited to 4 or 5 gears, you can utilise any pitch along the continuum from maximum to minimum. The pitch of the propeller may be controlled in flight to provide improved performance in each phase of flight. Typically you would take-off in a fine pitch (low gear) allowing your engine to develop reasonable revs, before increasing the pitch (change up gears) as you accelerated to your cruising speed. You'll end up with the propeller at a relatively coarse pitch, (high gear) allowing the miles to pass beneath you at a rapid rate, while your engine is gently ticking over at a comfortable speed.

This feature of a variable-pitch propeller will provide you with performance advantages, including:

- Reduced take-off roll and improved climb performance. Fine pitch allows the engine to reach maximum speed and hence maximum power at low airspeeds. Vital for take-off, climb, and for a go-around on landing.

- Improved fuel efficiency and greater range. Coarse pitch allows the desired aircraft speed to be maintained with a lower throttle setting and slower propeller speed, so maintaining efficiency and improving range.

- Higher top speed. Coarse pitch will ensure your engine does not overspeed while the propeller absorbs high power, producing a higher top speed.

- Steeper descent and shorter landing roll. With a fine pitch and low throttle setting, a slow turning propeller is able to add to the aircraft's drag, so slowing the aircraft quicker on landing.

Variable-pitch propellers actually come in a variety of versions. These different versions refer to the different ways that they are controlled, and include:

- Two-position propeller.
- Inflight-adjustable propeller.
- Automatic propeller.
- Constant-speed propeller.

A couple of these are now of historic interest only, so lets concentrate on the two most common options these days; the inflight-adjustable operation and the constant-speed propeller.

The inflight-adjustable propeller allows the pilot to directly vary the pitch of the propeller to the desired setting. Combined with the throttle control, this control allows a wide variety of power settings to be achieved. A range of airspeeds can be maintained while keeping the engine speed within limits. While rare in larger aircraft, the inflight-adjustable propeller is the most common type of variable-pitch propeller that is encountered in sport aviation.

When operated in manual mode, the Airmaster propeller is an example of an inflight-adjustable propeller.

Constant-speed propeller

The constant-speed propeller is a special case of variable pitch, which is considered in a family of its own, and offers particular operating benefits.

With constant speed control, the pitch of the variable-pitch propeller is changed automatically by a governor. After the pilot sets the desired engine/propeller speed with the propeller speed control, the governor acts to keep the propeller speed at the same value. If the governor detects the propeller speed increasing, it increases the pitch a little to bring the speed back within limits. If the governor detects the propeller speed decreasing, it decreases the pitch a little to bring the speed again back within limits. This operation may be compared to an automatic gearbox in an automobile, where the gears are changed automatically to keep the engine operating at a reasonable speed.

*(The governor or **constant speed unit [CSU]** may be an electronic device that detects the rotational speed of a slip-ring incorporated in the propeller hub, and controls operation of a servomotor/leadscrew pitch change actuator in the hub assembly. Or, it may be an hydraulic fly-ball governor attached to the engine, using engine oil to operate a hydraulic pitch change piston in the hub assembly. In the first case, the cockpit control device is likely to be knobs and switches. In the hydraulic system, the governor is likely to be cable operated from a cockpit*

lever — JB.)

A constant-speed propeller will automatically deliver you the advantages outlined above for variable-pitch propellers, with almost no control required from the pilot. Once a propeller/engine speed is selected, the pilot is able to control the power purely with the throttle (actually controlling the absolute pressure of the fuel/air mix in the intake manifold [MAP] which then determines power output) and the controller will act to keep the propeller/engine speed at the selected setting.

While allowing the pilot to ignore the propeller for most of the time, the pilot must still choose the most appropriate engine/propeller speed for the different phases of flight:

- Take-off, go-around and landing. A high speed setting is used when maximum power is needed for a short time such as on take-off. The high speed setting may also be used to keep the propeller pitch low during approach and landing, to provide the desired drag and be ready for a go-around should it be required.

- Climb and high speed cruise. A medium speed setting is used when high power is needed on a continuous basis, such as during an extended climb, or high speed cruise.

- Economic cruise. A low speed setting is used for a comfortable cruise with a low engine speed. This operation produces low fuel consumption and longer range, while the advantages of low noise and low engine wear are also enjoyed.

When operated in automatic mode, the Airmaster propeller is an example of a constant-speed propeller.

Special pitch modes

As well as the ability to vary the pitch of the propeller to optimise the aircraft performance, some variable-pitch propellers have some other special modes of operation that can be very useful in certain circumstances:

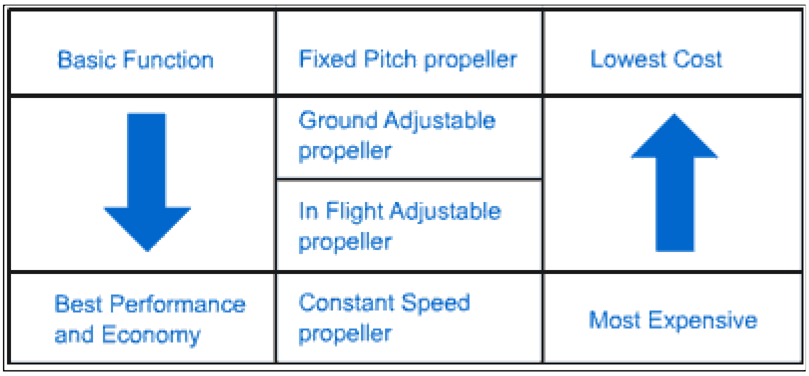
- Feather. A feathering propeller can alter the pitch of the blades up to almost 90 degrees. That is, the blade pitch is changed so that they have their leading edge pointing right into the direction of flight, offering minimum resistance to the airflow. This mode allows the propeller rotation to be stopped, without adding excessive drag to the aircraft. Feather may be used to improve the performance of the aircraft after the failure of an engine, but more usually in light aircraft it is used in motor glider applications. Here the engine is used to gain altitude, before the engine is switched off, the propeller feathered, and then gliding flight commenced.

- Reverse. A reversing pitch propeller can alter the pitch of the blades to a negative angle. That is, the blade pitch is changed so that they have their leading edge pointing slightly opposite to the direction of flight. This mode allows reverse thrust to be developed by the propeller. In larger commuter and transport aircraft this feature is often used to slow the aircraft rapidly after landing, but in sport aircraft it is more usually used to enhance manoeuvring on the ground. A popular application is in seaplanes, where the ability to manoeuvre backwards, and sometimes to reduce the thrust to nothing, is especially useful.

Summary

This overview was designed to assist the understanding of how the ability to control propeller pitch is used to categorise the different families of propeller design. More importantly it has illustrated that as we progress from one design family to another, we realise significant improvements in performance, effectiveness and efficiency.

While a family of propellers that offers better performance is likely to be more expensive to purchase, you can expect that over time the efficiency of a higher performance propeller will produce savings that will offset the initial cost. In addition your flying will be a more relaxed and enjoyable experience!



Basic Function	Fixed Pitch propeller	Lowest Cost
	Ground Adjustable propeller	
	In Flight Adjustable propeller	
Best Performance and Economy	Constant Speed propeller	Most Expensive

When deciding what type of propeller to buy for your aircraft, you have to weigh up the relative advantages and costs. To help, we can summarise the most common families of propellers, and make a simple comparison of their respective advantages in cost and capability.

Conclusion

If performance, economy and enjoyment are your goals, Constant Speed is the choice you should make.

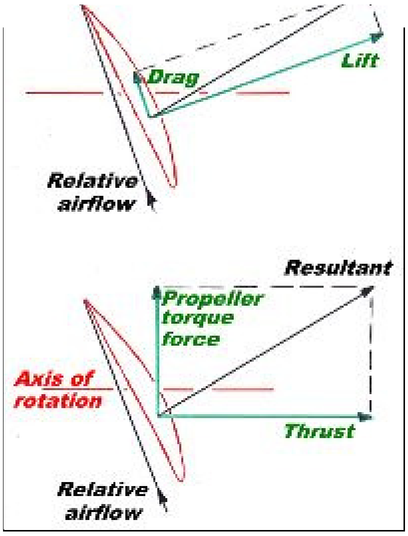
Read the FAQs on the Airmaster site.

Marcus Graney
Aeronautical Engineer
November 2000

5.4 Propeller theory

The forces

Propeller blades are constructed using aerofoil sections to produce an



aerodynamic force, in a similar manner to a wing. Consequently, the blades are subject to the same aerodynamics — induced drag, parasite drag, wingtip vortices, lift/drag ratios at varying aoa, pressure distribution changing with aoa, etc. There is a difference in application because, in flight, the propeller has rotational velocity added to the forward velocity. Thus, the flight path of any blade section is a spiral — a helical flight path.

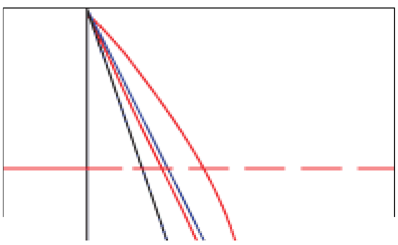
The diagram at left represents a blade section in flight and rotating about the shaft axis. Because of the different application, it doesn't serve much purpose to express the resultant aerodynamic force as we would for a wing; i.e. with the components acting perpendicular (lift) and parallel (drag) to that helical flight path, as in the upper figure. So, we resolve the aerodynamic force into the component acting forward and aligned with the aircraft's longitudinal axis as the thrust force, and that acting parallel to the direction of rotation as the propeller torque force.

As you see in the lower figure the component of the 'lift' acting in the rotational plane has now been added to the 'drag' to produce the 'propeller torque force' vector. The remaining forward-acting portion of 'lift' is then the thrust. That is why propeller efficiency is usually no greater than 80–85%; not all the 'lift' can be used as thrust, and the propeller torque force consumes quite a bit of the shaft horsepower. The propeller torque and the engine torque will be in balance when the engine is operating at constant rpm in flight.

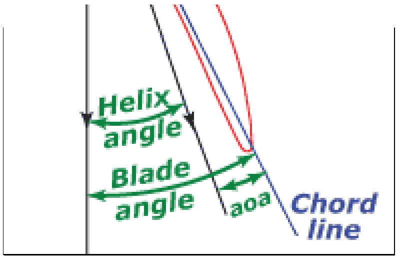
Centrifugal force imposes considerable tensile stress while trying to pull the blades from the hub. Torque reaction applies bending stress to the blades in the reverse direction of rotation while the thrust force tends to bend the outer sections of the blades forward. The centrifugal twisting moment tends to twist the blades to a decreased (finer) pitch and the aerodynamic twisting moment (similar to the wing pitching moment) tends to twist the blades to a coarser pitch. The air inflow at the face of the propeller disc also affects propeller dynamics.

Blade angle and pitch

Although all parts of the propeller, from the hub to the blade tips, have the same forward velocity, the rotational velocity — and thus the helical path of any blade station — will depend on its distance from the hub centre. Consequently, unless adjusted, the angle of attack will vary along the length of the blade. Propellers operate most efficiently when the aoa at each blade station is consistent (and, for propeller efficiency, that giving the best lift/drag ratio) over most of the blade, so a twist is built into the blades to achieve a more or less uniform aoa.



The **blade angle** is the angle the chord line of the aerofoil makes with the propeller's rotational plane and is expressed in degrees. Because of the twist, the blade angle will vary throughout



its length. So, normally the standard blade angle is measured at the blade station, 75% of the distance from the hub centre to the blade tip. The angle between the aerofoil chord line and the helical flight path (the relative airflow) at the blade station is the angle of attack and the angle between the helical flight path and the rotational plane is the angle of advance or helix angle. The aoa and helix angle vary with rotational and forward velocity.

The basic dimensions of propellers for light aircraft are usually stated in the form of number of blades, and diameter and pitch with values in inches; e.g. 3-blade 64" × 38". The pitch referred to is the geometric pitch that is calculated for any blade station, but usually the station at 75% radius.

Geometric pitch = the circumference (2πr) of the propeller disc at the blade station multiplied by the tangent of the blade angle. Thus, it is the distance the propeller — and aircraft — would advance during one revolution of the propeller if the blade section followed a path extrapolated along the blade angle.
e.g. For a blade station 24 inches from the hub centre (0.75r) and a 14° blade angle, the circumference = 2 × 3.14 × 24 = 150 inches, and tangent 14° = 0.25. Thus, the geometric pitch is 150 × 0.25 = 38 inches. Propellers are usually designed so that all blade stations have much the same geometric pitch.

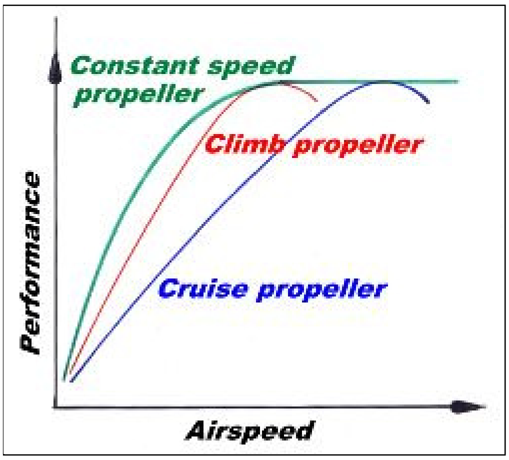
Designers may establish the **ideal pitch** of a propeller, which is the theoretical advance per revolution that would cause the blade aerofoil to be at the zero lift aoa; thus, it would generate no thrust and, ignoring drag, is the theoretical maximum achievable aircraft speed.

The velocity that the propeller imparts to the air flowing through its disc is the **slipstream**. **Slip** used to be described as the difference between the velocity of the air behind the propeller (i.e. accelerated by the propeller) and that of the aircraft. Nowadays, slip has several interpretations, most being aerodynamically unsatisfactory, but you might consider it to be the difference, expressed as a percentage, between the ideal pitch and the advance per revolution when the the propeller is working at maximum efficiency in converting engine power to thrust power. Slip in itself is not a measure of propeller efficiency; as stated previously, propeller efficiency is the ratio of the thrust power (thrust × aircraft velocity) output to the engine power input.

Pitch and velocity

The performance of aircraft fitted with fixed-pitch or ground-adjustable propellers is very much dependent on the chosen blade angle. Fixed-pitch propellers limit the rpm developed by the engine at low forward velocity, such as occurs during the take-off ground roll; they may also allow the engine rpm to exceed red-line maximum when the load on the engine is reduced, such as occurs in a shallow dive. Fixed-pitch propellers operate at best efficiency at one combination of shaft power and airspeed. Blade angle is usually chosen to produce maximum performance at a particular flight condition, for example:

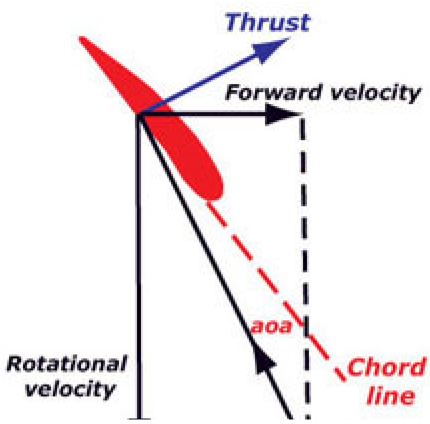
- Vy climb; i.e. a climb propeller
- Vc cruise; i.e. a cruise propeller.



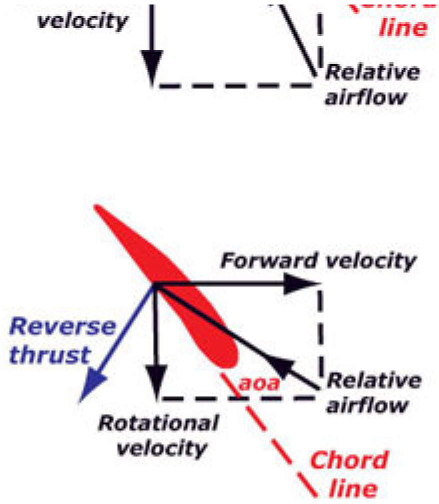
The climb propeller is usually chosen when the aircraft normally operates from a restricted airfield or in high density altitude conditions. The climb propeller will produce maximum efficiency at full throttle around the best rate of climb airspeed and will perform fairly well at take-off. But during the initial take-off acceleration, even the climb propeller may restrict the engine rpm to less than 75% power. The cruise propeller will achieve maximum efficiency at 75% power at airspeeds around the design cruising speed but aircraft take-off and climb performance will not be the optimum. The cruise propeller usually has a little more pitch than the standard propeller fitted to the aircraft. A high-speed propeller might be fitted when the aircraft is intended to be operating at, or above, rated power for short periods — in speed competition, for example.

A variable-pitch constant-speed propeller allows the engine to develop maximum rated power and rpm during the ground roll, and to develop full power throughout its normal rpm range. With a constant-speed propeller, the pilot controls the inlet manifold absolute pressure [**MAP**] with the throttle lever and the engine rpm with the rpm control lever or knob/switches. (MAP is the pressure of the air/fuel mixture being delivered to the cylinders and is usually measured in inches of mercury [in/Hg] rather than hectopascals. Standard sea-level barometric pressure is 29.92 in/Hg or 1013.2 hPa.) The aircraft flight manual usually provides the pilot with several combinations of rpm/MAP to achieve a particular power setting. For example, in one particular aircraft, the recommended combinations for 65% power at sea-level are 2100 rpm + 26 in/Hg MAP, or 2200 rpm + 25 in/Hg, or 2300 rpm + 24 in/Hg, or 2400 rpm + 23 in/Hg. So, you can use low rpm and high MAP, or high rpm and low MAP, to achieve exactly the same power output. The 2100 rpm/26 in/Hg low rpm/high MAP combination probably gives more efficient cylinder charging and better combustion plus less friction. The high MAP also acts as a cushion in the cylinders, reducing engine stress. Obviously, if a constant-speed propeller is fitted to an aircraft then an intake manifold pressure gauge — marked with the allowable engine operating ranges — must be fitted, otherwise excessive manifold pressure (which raises the cylinder compression pressure) may overstress the engine. Variable-pitch in-flight adjustable propellers also necessitate fitment of a manifold absolute pressure gauge.

The windmilling propeller



The angle of attack of a fixed-pitch propeller, and thus its thrust, depends on the forward speed of the aircraft and the rotational velocity. Following a non-catastrophic engine failure, the pilot tends to lower the nose so that forward airspeed is maintained while at the same time the rotational velocity of the engine/propeller is winding down. As the forward velocity remains more or less



unchanged while the rotational velocity is decreasing, the angle of attack must be continually decreasing. At some particular rpm, the angle of attack will become negative to the point where the lift component becomes negative (reverses) and the propeller autorotates; in effect, driving the dead engine as an air pump. This acts as greatly increased aerodynamic drag, which adversely affects the aircraft's L/D ratio and thus glide angles. The drag (including the reversed lift) is greater than that of a stationary propeller. The engine rotation may cause additional mechanical problems if oil supply is affected.

If the forward speed is increased, windmilling will increase. If forward speed is decreased, windmilling will decrease. Thus, the windmilling might be stopped by temporarily reducing airspeed probably to near stall — so that the reversed lift is decreased to the point where the engine airpump torque and friction will stop rotation. This is not something that should be attempted without ample height.

Should the PSRU fail in flight, the propeller is thereby disconnected from the engine and may 'freewheel' rather than 'windmill'.

In the diagram, the upper figure shows the forces associated with a section of a propeller blade operating normally. The lower figure shows the forces and the negative aoa associated with the propeller now windmilling at the same forward velocity.

A variable-pitch propeller may have a **feathering** facility, which turns the blades to the minimum drag position (i.e. the blades are more or less aligned fore and aft) and thus stops windmilling when the engine is no longer producing power. Such a feature is not usually fitted to a single-engine aircraft, but a few recreational aircraft are designed with wide span, high aspect ratio wings that provide L/D ratios around 30:1, and thus have excellent soaring capability. Such aircraft are usually fitted with a feathering propeller.

Some motor-gliders are designed with the engine/propeller unit mounted on a retractable pylon, so that when good atmospheric lift conditions exist the engine plus propeller can be stopped and stowed within the fuselage. See the TST-3 Alpin.

The runaway propeller

As a propeller system increases in complexity, then the possibilities for malfunction increase. A problem associated with constant-speed propellers is governor failure during flight which, in most installations, will cause the propeller blades to default to their fine pitch limit. This greatly reduces the load on the power plant, and the engine will immediately overspeed, particularly if in a shallow dive. Depending on the fine pitch limit setting, the rpm of an overspeeding engine — sometimes referred to as a 'runaway prop' — may quickly go way past red-line rpm and, unless immediate corrective action is taken, the engine is likely to self-destruct and/or the propeller blades break away from the hub due to the increased centrifugal force.

The corrective action is to immediately close the throttle and reduce to minimum flight speed by pulling the nose up. (But see 'Recovery from flight at excessive speed'.) Once everything is settled down, fly slowly, consistent with the fine pitch setting, to a suitable airfield using minimum throttle movements. *(The constant-speed propeller fitted to a competition aerobatic aircraft usually defaults to their coarse pitch limit to prevent overspeeding, but an immediate landing is required.)*

Propeller theory is complex and not appropriate to this Flight Theory guide, but the outline above at least introduces some of the everyday terms encountered.

The next module in this Flight Theory guide examines the tailplane stability and control surfaces.

Things that are handy to know

- The term 'brake horsepower' is a measure of the power delivered at the engine output shaft; measured by means of a dynamometer or similar braking device. The term 'shaft horsepower' [shp] is a measure of the engine power available at the propeller shaft. Generally it is the same as bhp but if the coupling is not direct drive — a propeller speed reduction unit [PSRU] is interposed between the crankshaft output and the propeller shaft as in the Rotax 912 — the shp will be a little less than bhp because of the power loss in driving the belt or gear driven PSRU.

- The use of the horsepower term for piston aero engines has successfully withstood metrication. To convert horsepower to watts multiply by 745.7 or by 0.75 to convert to kilowatts. When torque is expressed in newton metres, and engine speed in radians per second, power will be in watts.

- The stoichiometric (chemically correct) air/fuel mixture produces complete combustion of all the fuel and all the oxygen in the cylinder charge — and also the highest temperatures, which may be detrimental to the engine metallurgy. The stoichiometric air/fuel ratio for gasoline fuels is 14.7:1 by weight.

  Spark ignition engines provide best power with an air deficiency of 5–15% from stoichiometric — i.e. about 12–13:1 (rich) — and provide minimum fuel consumption with around 10% excess air; i.e. about 16:1 (lean).
  This indicates that the engine, at sea-level and using a stoichiometric mixture, would process about 8500 litres of air per litre of fuel. *(Avgas weighs 0.71 kg per litre, and air at sea-level weighs 1.225 kg per 1000 litres.)* The leaned mixture for best economy cruise is around 16:1 (9000 litres of air), and for maximum engine rich mixture performance, around 12:1 (7000 litres of air).

The Rotax 912 1.2 litre engine produces 75% power at 5000 rpm, and with a firing cycle every second revolution it would process 1.2 x 5000/2 = 3000 litres of air/fuel mixture per minute. The fuel used would be 3000/9000 = 0.33 litres/minute or around 20 litres/hour, at sea-level.

- Most four-stroke, normally aspirated, aero-engines between 80 and 400 hp have a specific fuel consumption close to 0.19 kg or 0.27 litres, per horsepower per hour (or 0.42 lbs/hp/hr). Then the Jabiru's engine, rated at 80 hp, but using only 65% for the 97 knot cruise, would consume 80 × 0.65 × 0.27 = 14 litres over 100 air nautical miles, or 7 air nautical miles per litre. *Note that you can create a little rule of thumb here that is applicable to most four-stroke engines — "the fuel burn, at 'performance cruise speed', is about one-fifth of the rated engine horsepower — in litres per hour." Thus, fuel burn for the Jabiru cruising at 75% power is 80/5 = 16 litres/hour. Two-stroke engines have to use a richer mixture to run cooler so, for such engines, add about 10% to the calculated result.*

Groundschool – Flight Theory Guide modules

Supplementary documents