CAP. 6 bis

APPENDICE SUL FUNZIONAMENTO DELLE ELICHE

Chapter 12
Propellers

INTRODUCTION

A piston engine requires a propeller to convert the power output (*engine torque*) of the engine into a useful straight-line force called **thrust**. There are two basic types of propeller, both with similar aerodynamics - fixed-pitch and variable-pitch (which uses a constant-speed unit). In this chapter, we discuss the basic principles as they apply to the fixed-pitch propeller, and then we cover the operation of constant speed (i.e. variable pitch) propellers.

TERMINOLOGY

Consider one section across a propeller blade at some distance from the hub or the centreline of rotation (Fig. 12-1). The blade section is a cambered aerofoil shape and it has a leading edge, a trailing edge and a chord line just like any other aerofoil. The cambered (lifting) side of the blade is called the **blade back** and the flatter side the **blade face.** The angle which the chord line makes with the plane of rotation is called the propeller **blade angle.** Note:

- For convenience, the chord line is normally taken to be the blade face. The actual chord line will depend on the cross-sectional shape of the blade.
- The blade angle, as we shall soon see, varies from a large angle at the blade root near the hub, gradually decreasing to a much smaller angle at the propeller tip.

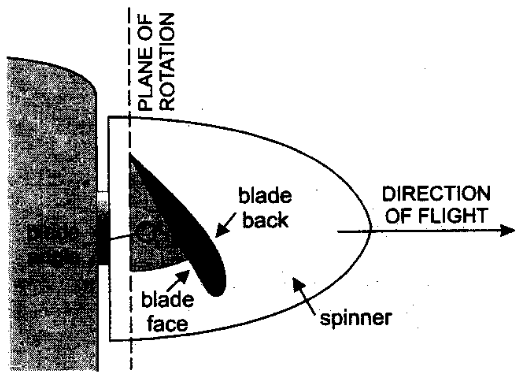


Fig. 12-1.
Propeller terminology.

BASIC PRINCIPLES

Since it is an aerofoil, the propeller blade generates an aerodynamic force in the same manner as any other aerofoil being moved through the air. In normal operation, when the propeller blade is rotated, the acceleration of the airflow over the forward cambered surface causes a reduced static pressure ahead of the blade. At the same time, when the blade has an angle of attack with the oncoming airflow, the flow is retarded by the blade face resulting in an increased static pressure. One of the results of these changes in pressure around the blade is that a forward **thrust** force is generated which pulls the aircraft along.

The development of thrust can also be considered in terms of the rearward movement of a mass of air. The changes in pressure around the rotating blades causes air to be drawn into the **propeller disc** (the circular area swept out by the blades) and accelerated in a roughly cylindrical area toward the rear (the slipstream). This rearward acceleration of the mass of air in the slipstream produces a forward reaction force on the blades in accordance with Newton's Third Law. The magnitude of this forward reaction force is dependent on the mass of the air and the acceleration it is given toward the rear. For a fixed-pitch propeller rotating at a given rpm, the lower the air density the less the mass of air which is accelerated rearward, and the lower the effectiveness of the propeller.

ROTATIONAL VELOCITY

Consider again just one of the propeller sections. If the aircraft is stationary, the motion of that propeller section will be purely rotational. The further out along the blade the section happens to be, the faster its rotational velocity and, the higher the rpm, the faster the rotational velocity of any given section.

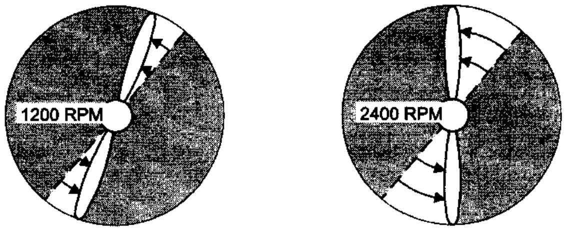


Fig.12-2. The speed of a blade section depends on radius and rpm.

FORWARD VELOCITY

As the aircraft moves forward in flight, the propeller section will have a forward velocity as well as the rotational velocity. When this forward motion is combined with the rotational motion, an overall velocity vector for the propeller blade section through the air can be obtained, as shown in Fig.12-3. The angle between this resultant velocity vector and the plane of rotation of the propeller blade is called the **helix angle** or the **pitch angle** or the **angle of advance.**

HELICAL MOTION

As a result of the combined rotational and forward velocity, each propeller blade section follows a 'corkscrew' path through the air called a helix. The easiest way to picture it is to consider the helix as the path which the trailing edge of the propeller section follows.

The relative airflow of each blade section is directly opposite to its own particular helical path through the air. The angle between the chord line of the blade section and the relative airflow is its angle of attack. *Note that the angle of attack plus the helix angle (pitch angle) make up the blade angle.*

When the aircraft is in flight, each propeller blade section will have the same forward velocity component. What will differ, however, is the rotational component of velocity - the further each blade section is from the propeller shaft, the faster it is moving. If the blade angle was the same along the whole length of the propeller (which of course it never is), then the angle of attack would continuously increase toward the tips. Under most conditions, this would result in the outer sections being operated at an angle of attack greater than the stalling angle.

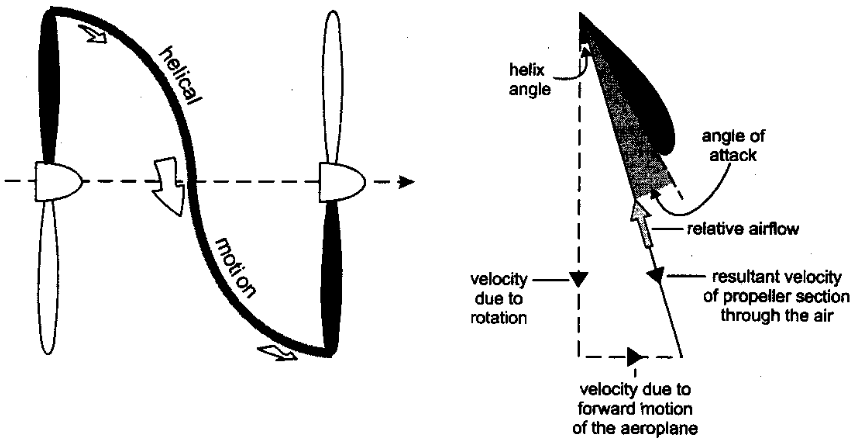


Fig.12-3. Each propeller section follows its own helical path.

Like all aerofoils, **each blade section has an angle of attack at which it is most efficient.** If the aircraft is designed to operate most efficiently at a given airspeed and engine (propeller) rpm, then the propeller must also be designed to have the most efficient angle of attack along its whole length, at that airspeed and rpm. To achieve this, the blade angle near the tip needs to be much smaller than the blade angle at the hub. This is known as **blade twist** or *helical twist*.

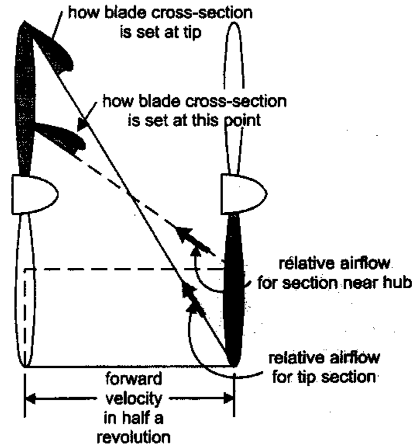


Fig.12-4. The propeller blade angle is made progressively smaller from hub to tip to provide efficient angles of attack along its whole length.

FORCES ACTING ON A BLADE SECTION

When an airflow is established around an aerofoil, the consequent pressure changes generate an aerodynamic force on the aerofoil. In the case of a wing, we resolve this total reaction into two components, one perpendicular to the relative airflow - *lift*, and the other parallel to the relative airflow - *drag*.

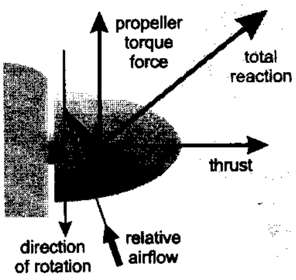


Fig.12-5. The forces acting on a propeller blade.

For the propeller however, where the relative airflow differs for each blade section, and where we are mainly concerned with generating thrust and not lift, it is no longer appropriate to talk in terms of lift and drag. Hence, it is more convenient to resolve the total reaction force into:

- one component perpendicular to the plane of rotation called **thrust;** and
- one component in the plane of rotation called the **propeller torque** force.

For our purposes, we can generally assume the direction perpendicular to the plane of propeller rotation to be the same as the direction of flight, and therefore, for the thrust to be considered as acting in the direction of flight.

The propeller torque is the resistance to motion in the plane of rotation.

For a wing, drag must be overcome to provide lift. For a propeller, the propeller torque must be overcome or balanced by the engine torque for the propeller to provide thrust. Opening the throttle increases engine power and engine torque, causing the propeller to rotate faster - until propeller torque builds up to the point where it comes into balance with engine torque and rpm stabilizes.

NOTE: If an aircraft with a fixed-pitch propeller is put into a dive, the relative airflow is changed and, because of the higher forward speed, the angle of attack is reduced over all propeller blade sections. Propeller torque is reduced and engine rpm will increase even though the throttle may not have been moved. Be aware that maximum rpm may be exceeded and power should be reduced as necessary to prevent this from happening.

THE RPM/AIRSPEED RELATIONSHIP

Consider again one section of a well-designed fixed-pitch propeller blade - at say, about 75% of the blade radius where, as we will see shortly, the thrust is produced most effectively. As illustrated at Fig.12-6, if the propeller rpm is constant, then the direction of the relative airflow and the angle of attack will be determined by the forward velocity.

As airspeed increases, the angle of attack of a fixed-pitch propeller blade at constant rpm will decrease. At some high airspeed , the angle of attack of the blade will be so reduced that little or no thrust will be produced. Hence, **for a given rpm, there will only be one forward velocity (true airspeed) at which the fixed-pitch propeller will operate at its most efficient angle of attack.**

The designer chooses a fixed-pitch propeller which has a best-efficiency airspeed/ rpm combination which matches the tasks for which the aircraft is designed. For an aircraft designed to lift heavy loads off short runways and to operate at fairly low airspeeds - e.g. for agricultural work - a fine-pitch propeller (with a small blade angle) is most suitable. For an aircraft designed to cruise long distances at reasonably high speeds, a coarser pitch propeller (i.e. with a larger blade angle) will be more suitable.

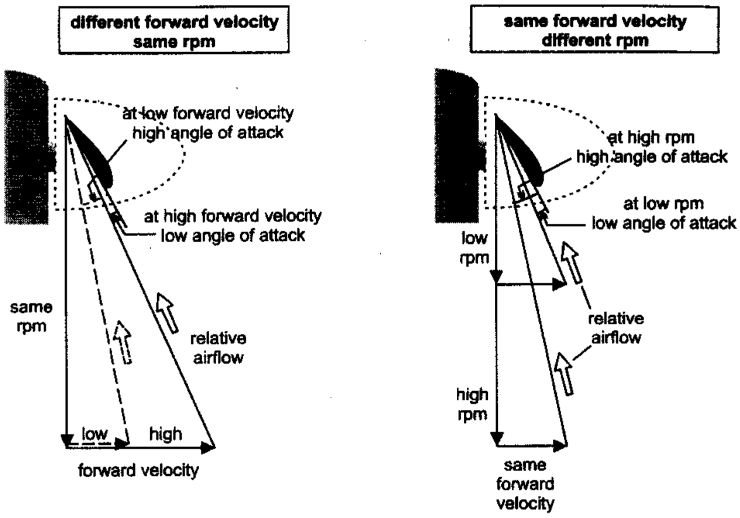


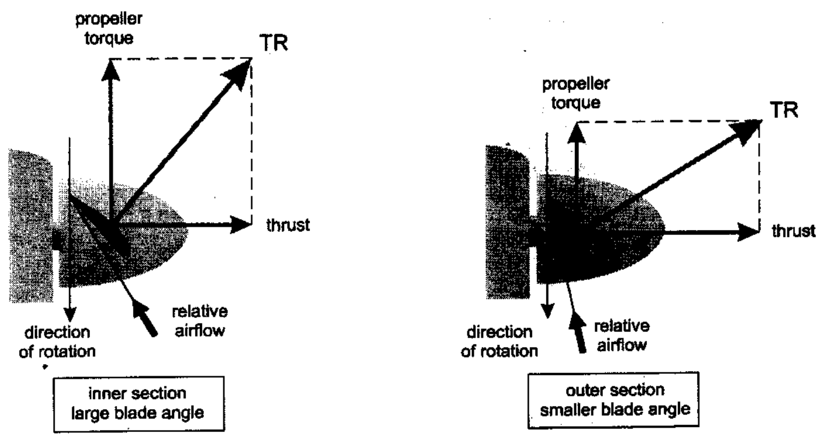
Fig.12-6. Fixed-pitch propeller: angle of attack varies with forward velocity, and with rpm.

EFFECTIVE BLADE SECTIONS

The most effective sections of the propeller blade in producing thrust are those which lie between 60 and 90% of the radius. The greatest useful thrust is produced at approximately 75% of the blade radius. When the blade angle of a propeller is quoted, it usually refers to the 75% station for this reason - *station* meaning *position on the blade.*

Near the hub, the propeller sections must be thick for structural strength, which may interfere with effective aerodynamic design. There is also the interference to the airflow from the engine and associated structures. Apart from this, the main reason for the inner propeller sections being less effective is that, of necessity, they must have a relatively high blade angle. This effectively tilts the local aerodynamic total reaction (TR) more toward the plane of rotation as shown in Fig. 12-7. In turn, this means that for these blade sections, less of the TR is resolved in the forward direction as thrust.

Fig. 12-7.



Again, as shown in Fig. 12-7, with their smaller blade angle, the TR of the outer sections is tilted further forward resulting in a greater proportion of the TR being resolved as thrust. However, toward the tips, the propeller blades become less effective, because:

- Vortices are formed at the propeller tips for the same reason as wing-tip vortices are formed. These increase the aerodynamic 'drag' and reduce the 'lift', resulting in a tilting back of the TR, with a consequent reduction in thrust and an increase in torque in the region of the tips.
- The propeller tip is the fastest travelling part of the aircraft since it has the highest rotational velocity compounded with the aircraft forward speed. At tip speeds approaching the local speed of sound, there is a significant increase in aerodynamic drag which, again, tilts the TR rearward and acts to increase the torque/reduce the thrust produced in the area of the tip.

PROPELLER PERFORMANCE

Propellers are unable to convert all of the power developed by the engine into useful thrust. There are losses involved in imparting motion (both translational and rotary) to the slipstream, and in the aerodynamic drag on the propeller. Under ideal conditions, a propeller will convert not more than about 90% of the brake horsepower delivered at the propeller shaft to useful thrust. In normal operating conditions, the efficiency of the propeller will typically vary between 50 and 85%.

Propeller efficiency is defined as the ratio of thrust horsepower (what the propeller produces) to brake horsepower (what is delivered to the propeller by the engine):

$$\text{propeller efficiency} = \frac{\text{thrust horsepower}}{\text{brake horsepower}} \%$$

Power is force x distance over time, hence thrust (horse)power in the above equation can be expressed as thrust x TAS, and propeller efficiency can also be written as:

$$\text{propeller efficiency} = \frac{\text{thrust x TAS}}{\text{brake power}}$$

(where brake power is the output of the engine, measured at the propeller shaft)

From the second of the above equations, note that propeller efficiency is zero under two conditions - (1) when aircraft has no forward speed (zero TAS) and (2) when there is no thrust produced. In practice, of course, the normal range of operation of a propeller falls within these two extremes. Fig. 12-8 shows typical curves of efficiency versus TAS for two different fixed-pitch propellers - one of fine pitch (small blade angles) and the other of coarse pitch (large blade angles).

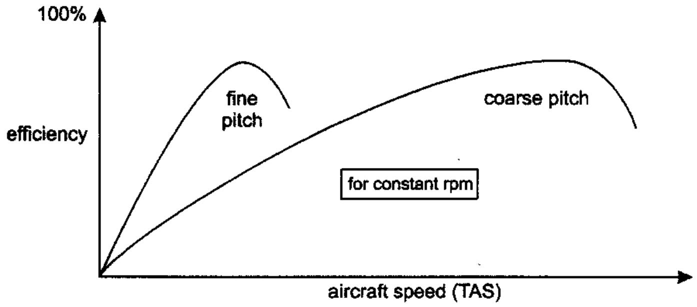


Fig. 12-8. Propeller efficiency curves.

Notes:

- For both propellers, efficiency is zero when the aircraft has no forward speed as has been previously explained. Although a high value of thrust can be developed when the aircraft is stationary, no useful work is done and the propeller is, by definition, inefficient until the aircraft begins to move and gains speed as a result.
- Given that each of the curves is for a constant rpm, the peak of efficiency for a fixed-pitch propeller is reached at one airspeed. This is a low airspeed in the case of the fine-pitch propeller and a high airspeed in the case of the coarse-pitch propeller.
- Once maximum efficiency is attained, any further increase in airspeed results in a relatively rapid decline in efficiency. This is because the angle of attack of the blades is being reduced to below the optimum, with a consequent reduction in thrust. It is possible, but only in a dive, to reach a speed where the blade angle of attack is reduced to the *zero-thrust* angle (which occurs just before the 'zero-lift' angle for the propeller aerofoil section). At this speed, no thrust is produced and efficiency is again reduced to zero.

SLIP

The distance which the propeller would theoretically move forward (or advance) in one revolution when it is giving no thrust is called the **experimental mean pitch.** The difference between this distance and the *actual* distance moved forward, is called **slip.** This difference is usually expressed as a percentage of the experimental mean pitch.

A propeller can be imagined as a type of screw - in fact, it was once commonly called an 'airscrew'. If an ordinary screw is turned through one revolution in a solid medium, it advances the same distance as its *pitch* (or distance between between the threads). When it is producing thrust however, a propeller cannot advance the same distance as its 'pitch'. As air is not a solid medium, when a propeller is turned in it, some of the air 'slips' backwards and the distance that it advances is less than its mean pitch. The amount of slip present is an indication of propeller efficiency.

Slip is shown diagrammatically in Fig. 12-9. Experiments have shown that maximum propeller efficiency is obtained when the slip is about 30%.

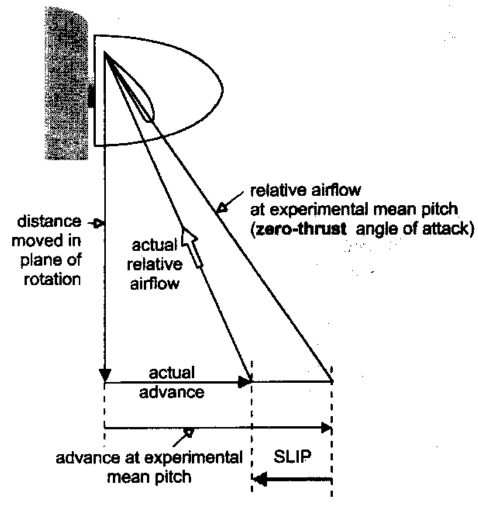


Fig. 12-9. Propeller slip.

Geometric Pitch

Geometric Pitch is the distance of advance at zero degrees angle of attack. It is a fixed quantity determined by the construction of the propeller and not by its performance. Note the difference between geometric pitch and experimental mean pitch as shown in Fig. 12-10. Geometric pitch is measured from the chord line and reflects the blade angle of a given section. Experimental mean pitch will occur when the blade sections have a small negative angle of attack - where the TR becomes aligned with the propeller torque and, therefore, no thrust is produced.

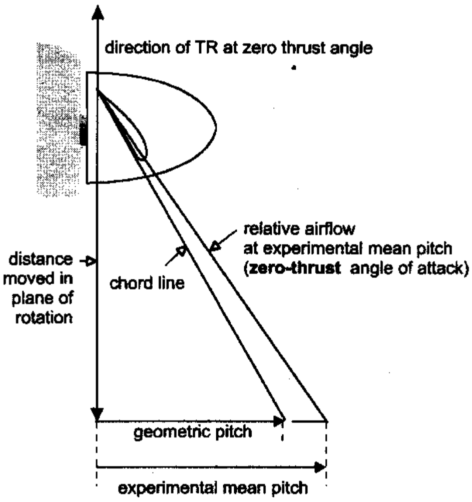


Fig.12-10. Geometric and experimental pitch.

Constant Speed Propellers

A fixed-pitch propeller operates at optimum efficiency only under one set of rpm and airspeed conditions. Because of this limitation, an early development in propeller technology was the two-pitch propeller - with a fine pitch setting for take-off and low speed operation, and a coarse pitch setting for higher airspeeds. This propeller was able to operate within two ranges of efficiency similar to those shown by the curves in Fig. 12-8, but within each range, it operated basically as a fixed-pitch propeller.

Subsequently, the modern-day constant-speed propeller was developed. This type of propeller has a blade angle which automatically adjusts to any position between two in-flight limits at the fine and coarse ends of its range. In normal operation, the pitch of the blades is determined by a mechanism called the **constant speed unit (CSU)** which governs the propeller speed at an rpm set by the pilot. By varying the pitch of the blades in this way, the constant-speed propeller can be operated at optimum efficiency over a much wider range of speeds than a fixed-pitch propeller.

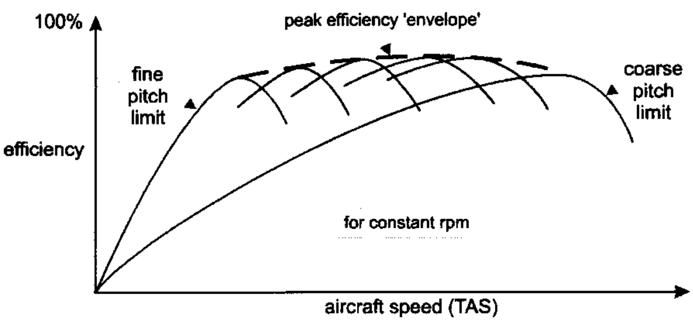
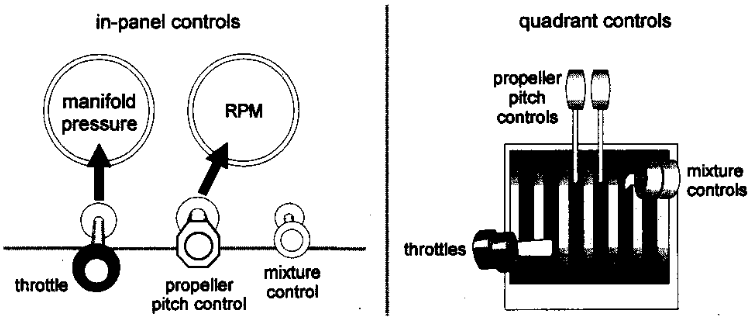


Fig. 12-11. Between its fine and coarse pitch limits, a constant-speed propeller can be operated at peak efficiency over a wide range of airspeeds.

Whereas with a fixed-pitch propeller, the pilot has only the throttle to control both engine power and propeller rpm, with a constant-speed propeller there are two controls:

- The propeller control (usually called the *pitch control*) which controls propeller rpm.
- The throttle to control manifold pressure (MP) and, therefore, the power developed by the engine.

Fig. 12-12. Typical control arrangements.



Moving the pitch control alters the rpm at which the propeller will be governed. Moving the throttle alters the amount of power which will be delivered to the propeller at the selected rpm. Controlling the power delivered by the engine and the thrust from the propeller is thus a matter of selecting certain combinations of propeller rpm and manifold pressure.

THE CONSTANT SPEED UNIT

The constant speed unit (CSU) - sometimes called a propeller control unit (PCU) - contains a governor which controls the rpm to that selected by the pilot. It does this by adjusting the pitch angle of the blades so that propeller torque remains matched (equal and opposite) to engine torque regardless of changes to airspeed and/or throttle setting.

Changes in Throttle Setting

If, at a given rpm setting, the throttle is opened (MP increased), engine torque will increase. As a result, the rpm will want to increase, but as soon as the CSU senses this it will increase the blade angle (coarsen the pitch) so that propeller torque is increased to match the increase in engine torque. The selected rpm will be maintained because the increase in engine power has been absorbed by the increased angle of attack of the blades. At this higher angle of attack, the propeller will produce more thrust and there will be a gain in performance - for example, in level flight - an increase in speed or, in a climb - an increased rate of climb.

Similarly, if the throttle is closed, the CSU will decrease the blade angle (fine the pitch) so that the selected rpm is maintained. With the decreased angle of attack of the blades, the propeller will produce less thrust.

Changes in Airspeed

If the airspeed is reduced by placing the aircraft in a climb without adjusting the throttle, propeller torque will *increase* (because the propeller blades have a higher angle of attack at the lower airspeed). As a result, the rpm will want to drop, but as soon as the CSU senses this, it will fine off the pitch to keep the propeller torque matched to engine torque thereby maintaining the selected rpm.

Similarly, if airspeed is increased by placing the aircraft in a dive without adjusting the throttle, the CSU automatically coarsens the pitch so that the selected rpm will be maintained.

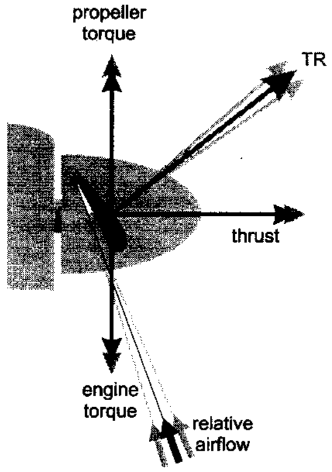


Fig. 12-13. When changes to power and/or airspeed occur, the direction of the relative airflow is affected. The CSU responds by changing the propeller blade angle so that propeller torque remains matched with engine torque at the rpm selected by the pilot.

The CSU can only govern propeller rpm in the manner just described, within certain limits. If engine power is reduced to a low setting, the blade angle will fine off until it reaches what is known as the fine-pitch stop. Thereafter, the propeller will act as a fixed-pitch propeller, with the rpm being controlled at low power settings by the throttle. If the throttle is opened and the rpm rise to the figure previously selected with the pitch control, the CSU will once again take over and begin to govern the rpm at that figure.

The design of constant-speed propellers is such that, provided they are operated within the range of in-flight rpm/MP settings recommended in the Pilot's Operating Handbook, they will remain working at or close to their best angle of attack and thus with optimum efficiency for the conditions.

OPERATION OF CONSTANT SPEED PROPELLERS

Constant-speed propellers are normally operated on the ground with the pitch control in the *FULL FINE* position. As a part of the pre-flight checks, the CSU is normally 'exercised' before each flight on cold days, otherwise before the first flight of the day. This is achieved by running the engine up to the rpm specified by the manufacturer (normally about 1800 - 2000 rpm) and then cycling the pitch control slowly from *FULL FINE* to *COARSE* and back again two or three times. The rpm should decrease (normally not more than 500) and increase again in concert with the movement of the pitch control. The object of exercising the CSU in this manner is to enable warm oil to circulate through the hydraulic pitch changing mechanism. If this is not done, cold and viscous oil may result in sluggish operation of the unit and the CSU may not be able to control rpm properly on the take-off and climb-out.

As part of the pre take-off checks, ensure that the pitch control is placed in the *FULL FINE* position for take-off. If this is not done and an attempt is made to take off with the pitch control in a coarse position, the required rpm and full thrust will not be developed during the take-off run. At best, the take-off distance will be significantly increased and there will be a risk of damaging the engine through 'overboosting' and detonation. At worst, the aircraft may simply not become airborne in the distance available!

At all times, operate the engine within the range of rpm/MP settings recommended in the Pilot's Operating Handbook. Operation at a higher MP than that recommended for the rpm selected, can lead to high cylinder head temperatures and detonation.

Changing power settings

To increase power (if it is desired to operate at higher rpm):

- **first increase rpm** with the pitch control;
- **then increase MP** to the desired value with the throttle.

To decrease power (if it is desired to operate at lower rpm):

- **first reduce MP** with the throttle;
- **then reduce rpm** with the pitch control.

As altitude is changed with an unsupercharged engine, so will MP at the rate of about 1" Hg per 1000 ft. The selected rpm should remain constant, but the throttle will have to be occasionally adjusted to maintain a given MP (opened in a climb, closed in a descent).

During the pre-landing checks, ensure the pitch control is set to *FULL FINE* so that full power will be available in the event of a go-around.

OTHER MODES OF OPERATION

In addition to providing more efficient operation over a wide range of airspeeds and engine power, with some constant-speed propellers the advantages of being able to vary the pitch are extended to:

- The ability to be feathered in flight to avoid 'windmilling' drag and the possibility of further damaging an engine which has failed.
- The ability to be placed in ground-fine pitch or reverse pitch, to provide aerodynamic braking during the landing run.

Windmilling

If there is a loss of engine torque to the propeller, the CSU will fine off the pitch in an attempt to maintain the rpm selected at the time. A point is soon reached where the relative airflow approaches the blade at a 'negative' angle of attack which is large enough to produce a TR in the reverse direction to normal - refer to Fig. 12-14. The torque component of this reversed TR now acts in the same direction as engine torque would normally act and will drive (i.e. 'windmill') the engine, even though no power is being produced. The reversed thrust component (windmilling drag) also now acts in the same direction as aircraft drag. This extra drag from a windmilling engine can be substantial, and is roughly equivalent to a flat disc with the same diameter as the propeller being placed at right angles to the relative airflow.

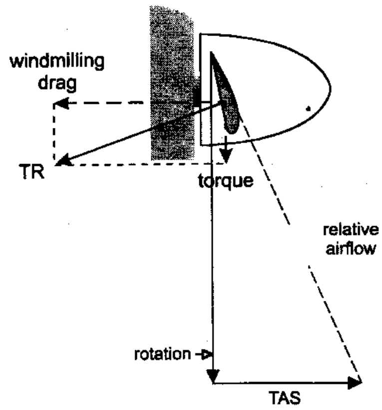


Fig. 12-14. The forces acting on a windmilling propeller.

Feathering

It is clearly a big advantage to be able to prevent windmilling drag following an engine failure. The extra drag from this cause can limit the 'engine-out' range, degrade performance, and create control difficulties on a multi-engined aircraft. Additionally, with windmilling torque continuing to drive a possibly damaged engine, there is the eventual risk of seizure or fire.

Feathering involves turning the blades to the angle of attack with the oncoming airflow at which no net propeller torque is produced. In this position, the blade sections nearer the hub will have a 'positive' angle of attack, while those nearer the tips will have a 'negative' angle - 'positive' and 'negative' lift will cancel out and no turning moment on the propeller will be generated (Fig, 12-15). When the propeller is in the feathered position, it will produce the minimum amount of drag.

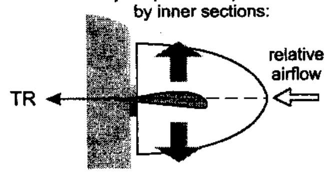


Fig. 12-15. A feathered propeller.

NOTE: For those constant-speed propellers which do not have a feathering capability, it is important that the pitch control is placed in the *FULL COARSE* position following an engine failure. This will reduce the drag from the 'dead engine' to the minimum, even if for some reason, it does not continue to turn over.

Reverse Thrust

If the propeller blades are turned through the fine pitch stop to a blade angle of about minus 20° and power is applied, reverse thrust is obtained. The blade sections are working relatively inefficiently at a negative angle of attack. The forces acting on the blade when operating in reverse pitch are shown in Fig. 12-16.

As the blade is being rotated below the normal fine pitch stop to obtain the reverse thrust angle, it must pass through an arc in which the blade angles are small and negative. During the transition through this arc, the forces acting on the propeller will be as shown in Fig. 12-14, i.e., it will be in the windmilling mode. If power is applied when the propeller angle is in this arc, an overspeed is likely. Mechanical devices are therefore used to prevent the application of power until the propeller blades have been turned safely into the reverse pitch range.

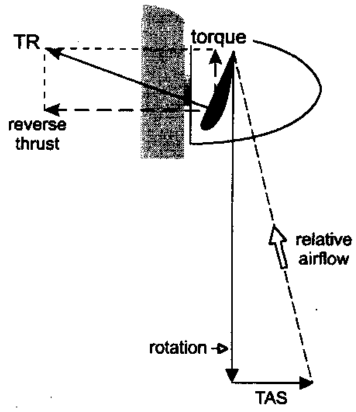


Fig. 12-16. Reverse thrust.

PROPELLER TWISTING MOMENTS

Considerable stresses are placed on the propeller blades and pitch changing mechanism in flight. The most important of these are:

- centrifugal force;
- centrifugal twisting moment, and
- aerodynamic twisting moment.

Centrifugal Force

The blades of a rotating propeller have mass and are turning on a circular path about the propeller hub. To keep the blades turning on their circular path, a centripetal force must be applied toward the centre of rotation. This force, proportional to the mass of each blade and the square of its rotational velocity, is of course, applied to the blade at the attachment point of the blade root with the CSU.

The *centrifugal force* on the blade is the reaction (in accordance with Newton's Third Law) to the centripetal force required to keep it turning in its circular path. As much as CSU attachment point has to 'pull' on the blade to keep it rotating in a circle, the blade reacts by 'pulling' in the opposite direction with the same force. This centrifugal force (which is acting as if to stretch the blades and pull them out of their 'sockets') can be very strong, especially at high rpm.

Centrifugal Twisting Moment (CTM)

Consider the propeller blade in Fig. 12-17. When the propeller is rotating, the centrifugal force which affects each part of the blade originates from the centre of rotation. For example, that part of the blade at X on the leading edge of the blade is subject to the force X-A, and that part at point Y is subject to force Y-B.

Each of these forces can be resolved into the following components:

- Forces in line with the span of the blade (parallel to the pitch-change axis) which try to pull the blade out of its 'socket'. These spanwise components on the leading and trailing edges of the blade are shown as X-C and Y-D.

- Forces at right angles to the span (and pitch-change axis) which try to pull the blade into fine pitch. These chordwise components result in the **centrifugal twisting moment (CTM).** To visualise the action of the CTM, consider the end view of the blade section as well as the plan view shown in Fig. 12-17. It can be seen that the forces on the leading and trailing edges, represented by X-E and Y-F respectively, form a couple about the pitch-change axis which attempts to pull the blade into fine pitch.

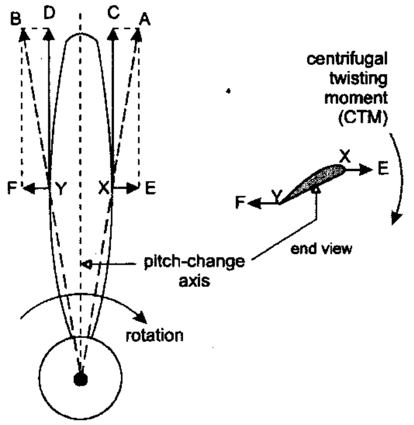


Fig. 12-17.
Centrifugal twisting moment.

In constant-speed propellers, The CTM places a greater demand on the pitch changing mechanism when increasing blade angle (moving to coarse) and less demand when decreasing the angle (moving to fine). The strength of the CTM is influenced by the shape of the propeller - those with wide blades and a greater chordwise distribution of mass, will have a stronger CTM and a greater tendency to go into fine pitch, than propellers with narrow blades.

Aerodynamic Twisting Moment (ATM)

An **aerodynamic twisting moment (ATM)** arises whenever the aerodynamic total reaction force (TR) does not act on a line through the pitch-change axis. In normal operation, the centre of pressure of the blade is usually forward of the pitch change axis resulting in an ATM which tends to coarsen the blade angle (i.e. turn it in the opposite direction to the CTM). But, as the ATM is usually much weaker, it only partially offsets the CTM.

When a propeller is windmilling however, the ATM is reversed and acts in the same direction as the CTM - i.e. both act to fine off the propeller. In a steep dive at low power, the combined effect of the CTM and ATM may be strong enough to prevent the CSU from moving the blades to a coarse position as speed is gained, resulting in an engine overspeed.

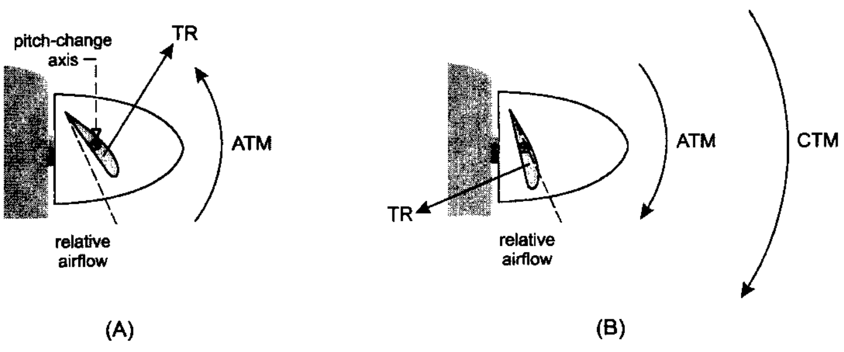


Fig. 12-16. (A) Aerodynamic twisting moment, and (B) twisting moments on a windmilling propeller.