Why

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As the pilot moves from the low-powered and slow trainer aircraft into the modern high-performance single-engine or twin aircraft, he will sooner or later encounter a device with the impressive name of *constant-speed-controllable variable-pitch propeller.* This may be successfully ignored by learning two or three standard settings of the pitch control, but somewhat better performance and a good deal of satisfaction may be gained by learning just what goes on, and why, inside the hub of this interesting gadget.

First, let us look at the fundamental concepts of propeller operation in order to see the dilemma faced by the propeller designer. Most features of propeller operation can be understood by considering the propeller to be a miniature rotating airfoil arranged so as to convert the engine torque into useful thrust to move the airplane.

In Figure 1, we see a cross section of this airfoil with its two components of motion through the air. One component, in the plane of rotation of the propeller, is due to the rotational velocity of the blade section. The other is due to the forward motion of the aircraft, and is perpendicular to the plane of rotation of the propeller. The sum of these two motions represents the total velocity of the airfoil section and lies at an angle known as the effective pitch angle to the plane of rotation. The relative wind on the airfoil is opposite the total velocity of the blade section. Now the propeller section produces two forces, a *lift* perpendicular to the relative wind, and a *drag* force parallel to the relative wind.

The magnitudes of these forces depend on the *angle of attack* of the propeller section, or the blade angle with respect to the relative wind. It turns out that the lift force is the one which converts the rotary engine power directly to the thrust power required to pull the airplane. The drag force increases the torque on the engine while reducing the available thrust and keeps us from having a perfectly efficient conversion of engine torque to thrust.

The object of propeller design is to provide just enough lift force in the propeller to handle the maximum available engine power, while minimizing the drag force. For typical airfoil sections the maximum lift/drag occurs around a 3° angle of attack, so the propeller is built to have a blade angle (angle of blade chord line with respect to plane of rotation) about 3° greater than the effective pitch angle. Typically, this yields a propeller with an efficiency of about 86% (100 h.p. from the engine results in about 86 h.p. in propeller thrust).

Notice that the correct blade angle depends on the forward speed of the airplane and on the rotational speed of the propeller blade section. The first consequence of this is that the blade angle varies along the length of the blade. Consider a 72-inch propeller rotating at 2,500 r.p.m. with a true forward speed of 150 m.p.h. (220 feet per second). At the tip the rotational speed is 785 feet per second (tip moves 18.9 feet around the circle 41.6 times per second), and the relative wind therefore arrives at an angle of 15½° from the plane of rotation. Thus the blade angle at the tip is set around 18½°.

At a point one foot from the hub, however, the rotational speed is only 262 feet per second because this blade section has less distance to travel per revolution. Here the relative magnitudes of the forward and rotational speeds are such that the angle of the relative wind is 40°, and the blade angle would thus be about 43°. This twist from a relatively small blade angle near the tip to a much higher angle near the hub is readily evident on any propeller.

The effect of a change in forward speed on the direction of the relative wind also causes the thrust developed at a particular r.p.m. to be quite strongly dependent on airspeed. Suppose we tried to increase the airspeed in the above example by 10% to 165 m.p.h. while still maintaining 2,500 r.p.m. The increased forward speed increases the angle of the effective wind at the 36-inch radius station to 16.6°, so the angle of attack of the blade is reduced to less than 2° and the thrust reduced accordingly. Moreover, at one foot radius the angle of the relative wind is increased to 43°, so the angle of attack (and thus the thrust devoloped by this part of the blade) becomes zero. At radii smaller than one foot the angle of attack becomes negative, so the relative wind is actually blowing on the *front* of the blade. Thus, these parts of the propeller, rather than producing thrust, are actually acting as a brake on the airplane.

As the speed increases still further, more and more of the propeller begins acting to slow, rather than to pull, the airplane. This fact contributes to the excellent airspeed stability of fixed-pitch-propeller type aircraft.

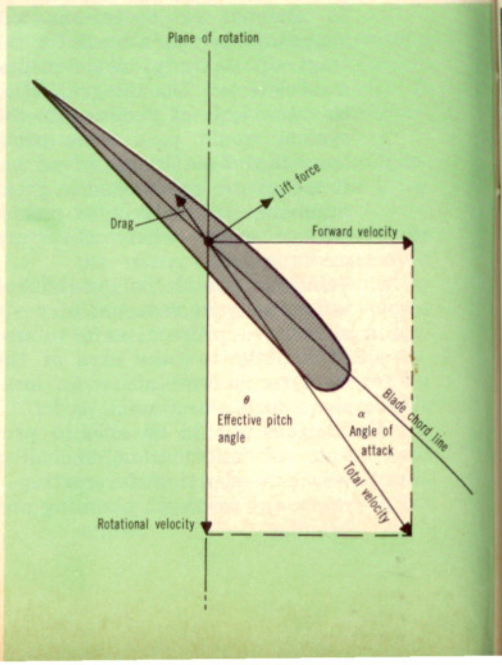
Of course the natural tendency of the propeller is to speed up as the forward speed of the aircraft increases and reduces the angle of attack (and therefore the load) on the propeller. And in fact if the propeller r.p.m. were also increased by 10% to 2,750 r.p.m. as the airspeed increased by 10%, the angle of attack of the blades would not change. The propeller would still be operating in its most efficient range, and the power available from it would go up in the same way as the power required to pull the airplane faster (assuming the engine were capable of supplying the additional power).

However, it is difficult to design aircraft engines to operate over a wide range of speeds, so this is not a particularly practical means of operating an aircraft over a wide airspeed range. This is one reason for using variable-pitch propellers, so the angle of attack of the propeller blades may be adjusted properly over a fairly wide true-airspeed range while still maintaining reasonably constant engine speed.

The other major factor requiring the use of variable-pitch propellers is the trade-off between takeoff and cruise performance. At very low forward speeds at the beginning of the takeoff run the angle of attack of the propeller blades is nearly equal to the full-blade angle. These large angles of attack drastically increase the drag force and reduce the efficiency of the propeller. In fact, since airfoils typically stall at about 18° angle of attack, a large portion of the propeller is actually stalled at the beginning of the takeoff run. This accounts for the fact that maximum acceleration is generally felt sometime during the takeoff run after the propeller begins to couple efficiently rather than right at the beginning of the run.

Thus for good takeoff performance it is desirable to keep the blade angle small to reduce the drag, while still maintaining enough lift force to use all available engine power. This is in direct conflict with the need for large-blade angles for high-speed cruise operation. The required compromise is not too difficult for J-3 category airplanes, although it is easy to notice the difference in takeoff performance be-

Figure 1—Motion and forces of propeller blade section



Variable-Pitch Propellers?

Better performance may be obtained by knowing what goes on—and why —inside the hub of your airplane's 'fan'

tween "climb" (low blade pitch) and "cruise" (high pitch) propellers on these aircraft. However, in modern aircraft with cruising speeds of 150 m.p.h. or even 200 m.p.h., the conflict is just too great to tolerate. When the propeller is built for a sufficiently high critical cruising speed, the takeoff performance is seriously impaired. Clearly, what is needed is a propeller which can somehow have a low-pitch angle for takeoff and climb, yet switch to a higher pitch angle for maximum cruising performance.

Variable-pitch propellers for lightplanes almost invariably are of the hydraulic type, operating by means of engine oil directed into the propeller hub through some control mechanism. A typical design (Hartzell) is illustrated in Figures 2 and 3. Each blade is clamped to the hub through a ball thrust bearing assembly such that the blade can be twisted through a considerable pitch angle. A small counterweight is attached to each of the blade clamps extending roughly perpendicularly from the blade face. As the propeller rotates, centrifugal force acting on the counterweight tends to pull it around into the plane of rotation, thus moving the blades into high pitch.

The blade may be moved back toward low pitch by pumping oil into the interior of the hub, forcing forward the piston at the front of the hub. This piston is connected by means of actuating links to the blade clamps near the counterweights. Thus, extending the piston works against the force on the counterweights and brings the blades back into low pitch. This meets the requirements for a two-position variable pitch propeller. For takeoff and climb, where a low pitch is required, the pilot directs engine oil into the propeller hub, extending the piston and forcing the blades into their low-pitch position. For high-speed cruising the oil is drained from the propeller hub, allowing the counterweights to pull the blades into their high-pitch position.

McCauley propellers (and some Hartzells) differ from the Hartzell described above in that they do not have counterweights, and the centrifugal force on the propeller blades (assisted by a spring inside the hub) tends to move the blade into the low-pitch position. The piston and linkage are then arranged to move the blades into high pitch when oil pressure is applied. The main operational difference is that the McCauley will move into low pitch and the Hartzell into high pitch if oil pressure is lost due to a malfunction. The difference is somewhat academic on single-engine aircraft, since loss of oil pressure probably means loss of the engine. However, the Hartzell design is a little better adapted for addition of feathering systems for multi-engine aircraft.

A more sophisticated system which allows for control of the pitch throughout its range, rather than just two pitch positions, is the constant-speed propeller. This consists of a variable pitch propeller of the same basic design as described above, plus a governor which senses the engine speed and controls the flow of oil to the propeller in order to produce the correct r.p.m. Figure 4 shows a simplified cross section of a Woodward-type governor. The flyweight head is driven from the engine shaft, so that the centrifugal

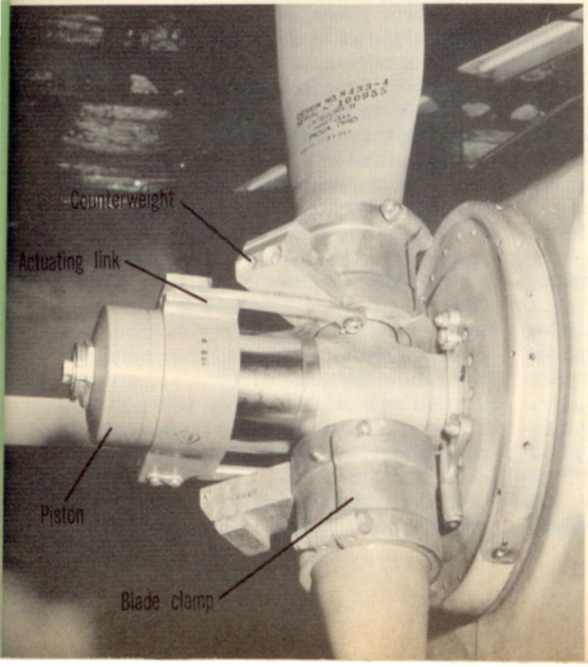


Figure 2—Hub assembly of variable-pitch propeller
Photo by Hartzell Propellers Inc.

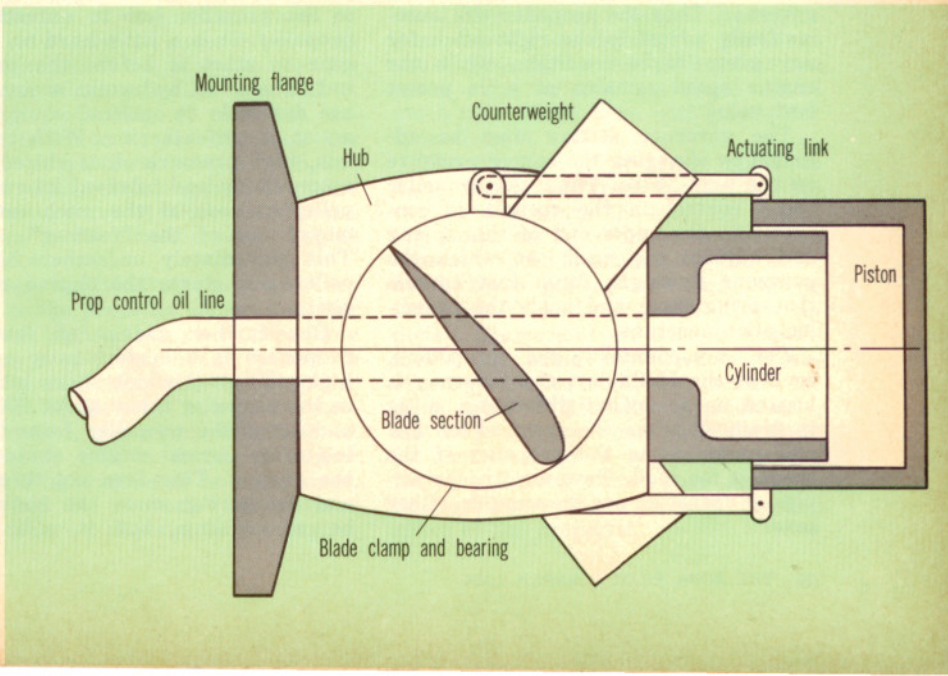


Figure 3—Simplified cutway view of variable-pitch propeller

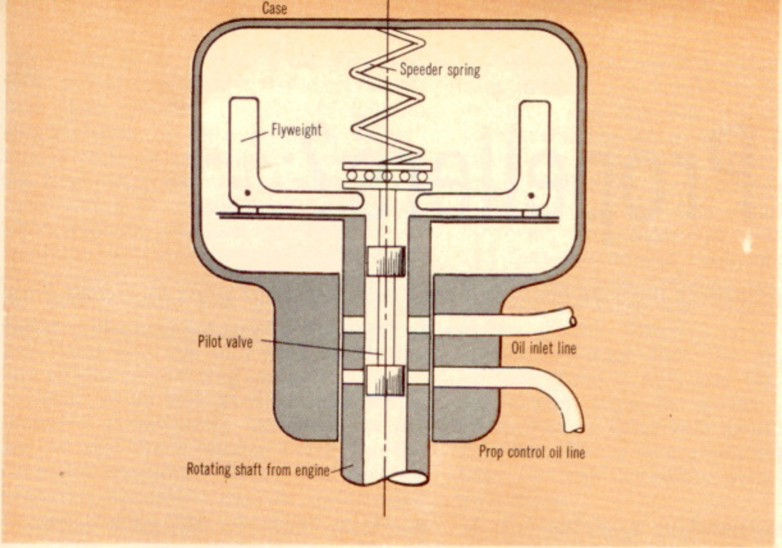


Figure 4—Simplified cutaway of Woodward-type governor

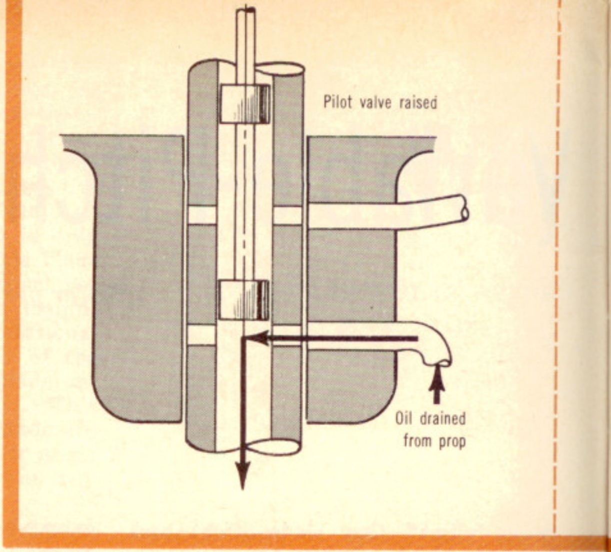


Figure 4a—Propeller overspeed

force on the flyweights depends on the engine speed. As the centrifugal force pulls the flyweights out, they tend to lift the pilot valve shaft. Counteracting this is a spring forcing the pilot valve back down. If the engine is running at the desired speed the pilot valve will just cover the propeller control-line port so that oil can neither flow to nor from the propeller.

If the engine speed is higher than desired, the pilot valve is lifted higher by the flyweights as shown in Figure 4a. This allows oil to drain from the propeller piston back into the engine sump. The propeller counterweights then increase the propeller pitch, which in turn produces more load on the engine and decreases the engine speed. If the engine speed is too low the pilot valve is lowered as in Figure 4b and high-pressure oil is admitted to the propeller control line. The propeller pitch is then decreased until the proper speed is reached. These changes of propeller pitch are entirely automatic, always bringing the propeller speed to that determined by the setting of the governor. Thus the propeller will automatically adjust to the right pitch for any given flight condition, while the engine speed remains at some preset best value.

The governor setting may be adjusted by changing the spring pressure on the pilot valve. Thus, the propeller speed control in the cockpit is connected to the upper end of this spring and adjusts the r.p.m. at which the governor flyweight force just cancels the spring force and holds the propeller pitch constant.

For non-counterweight propellers, such as the McCauley, the governor is hooked up somewhat differently so as to drain oil when the speed is too low and pump oil to the propeller if the speed is too high. However, the principles of operation are the same in either case.

Variable-pitch propellers on multi-engine aircraft must also provide for feathering, or rotation of the blade so that its edge lines up with the path of flight for minimum drag in engine-out situations. Feathering in the Hartzell is accomplished by opening a bypass in the governor from the propeller control line back to the engine drain line, when the prop pitch control is moved past the low-r.p.m. limit. The oil is then drained from the propeller piston, allowing the counterweights (assisted by a feathering spring in the propeller hub) to rotate the blades into the feathered position.

One interesting feature of this method of feathering is that a loss of engine oil pressure will automatically feather the propeller without any action by the pilot. This could save the engine from damage due to further operation without oil pressure.

Unfeathering for engine restart is accomplished by moving the pitch control back into the normal range. When the engine is then restarted in the normal manner, engine oil will flow back to the propeller hub to unfeather the propeller. It is a little hard on the engine to start it before the propeller unfeathers, so hydraulic accumulators are available as optional equipment to assist in unfeathering. With this system, high pressure oil is stored in the accumulator and released into the propeller as soon as the pitch control is moved out of the "feather" position. This immediately unfeathers the propeller and starts the engine rotating again.

One further gadget on feathering propellers is a centrifugally operated high-pitch stop which slides into place in the propeller below about 600 r.p.m. and keeps the propeller from feathering after normal engine shutdown on the ground. This does not affect normal feathering since the engine will be windmilling, but it will inhibit feathering if an engine seizure occurs before an attempt to feather is made.

Pre-takeoff check of propeller operation consists of running up to around 1,800 r.p.m. with prop pitch control in "high r.p.m." position. This leaves the propeller against the low-pitch stops and allows magneto and carb heat checks against the r.p.m. The propeller control is then pulled toward the low r.p.m. position until a sharp drop in r.p.m. occurs, then is returned to the full-high-r.p.m. position for takeoff. On a twin the prop control is moved into the "feather" position just long enough to demonstrate that feathering has started, then returned to the normal range. A final check on adjustment is made by observing whether the r.p.m. comes up to within 20 to 40 r.p.m. of engine red-line as soon as full power is applied on the takeoff run and stays there throughout the takeoff.

Following takeoff, the propeller control should be pulled back to climb r.p.m. after the manifold pressure has been reduced for climb. In general, for power reductions the throttle should be pulled back before the r.p.m. is reduced, to avoid abnormally high pitch angles and undue strain on the engine and on the propeller blades. Similarly for power increases such as from cruise to climb, advance the propeller r.p.m. first, then advance the throttle.

The propeller control should also be in the full-high-r.p.m. position for landing to provide some braking action and to be prepared for application of maximum power if necessary for a go-around. In order to avoid high engine r.p.m. during the approach, moving the control into full-high-r.p.m. may be delayed until after the last power reduction on final, but the propeller should be in at least climb r.p.m. position throughout the approach in case a go-around is required.

Cruise operation of a constant-speed propeller gives the pilot considerable

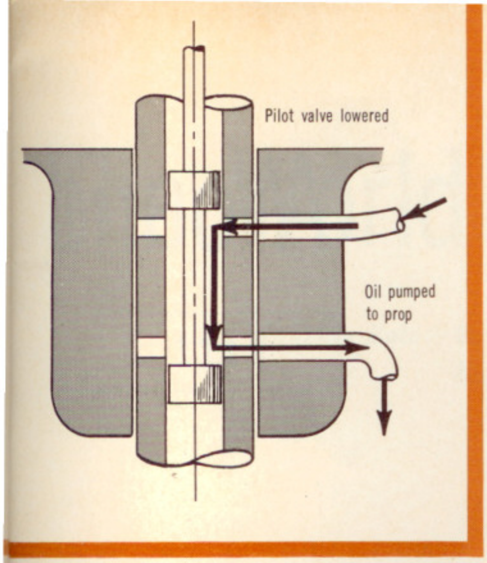


Figure 4b—Propeller underspeed

room for choice, since a number of combinations of r.p.m. and manifold pressure will yield the same percentage power. The main rule-of-thumb to be remembered is that the manifold pressure in inches should not generally exceed the r.p.m. in hundreds except for takeoff. Again, this is to avoid excessively large propeller angles of attack and resultant stresses on the propeller and engine.

For maximum efficiency and minimum fuel consumption, Piper recommends using a relatively low r.p.m. and whatever manifold pressure is needed to obtain the desired percentage power, consistent with the above rule. However, they point out that the choice of r.p.m. should also be based on noise and vibration, since vibration or excessive noise also cost fuel as well as damaging the engine and airframe. Some operators feel that it is advisable to use a high cruising r.p.m. and correspondingly lower manifold pressure for all operations, including low power settings. The reason is that reduced vibration due to the smoother engine operation at high r.p.m. saves more in maintenance costs than is lost in the slightly higher specific fuel consumption.

Another factor that often dictates the use of a high r.p.m. is high-altitude operation. The critical altitude (the altitude at which the desired power can be obtained only at full throttle) of an engine increases with engine r.p.m. For example, cruise at 75% power at 8,000 feet can be obtained at 2,400 r.p.m., while it is not possible at 2,200 r.p.m. in a typical engine.

Thus, the proper procedure for setting up cruising power is to select the approximate r.p.m. desired—based on the above considerations and within the manufacturers recommended range—and look in the vicinity of this r.p.m. for the region of smoothest operation. Then using the column corresponding to this r.p.m., or interpolating between columns if necessary, on the power chart for the aircraft, and the desired percentage power, look up the necessary manifold pressure in the row opposite the density altitude. If the required pressure is unduly high, select a higher r.p.m. and try again.

Leaning the mixture presents a bit of a problem, since it is no longer possible to adjust the mixture for maximum r.p.m. with a constant-speed propeller. The easy way out of course is to lean until roughness appears, then push the mixture control back in until smooth operation is restored. A more complicated method used by some people is to reduce throttle until the engine r.p.m. falls off about 100 r.p.m., indicating that the propeller is against the low pitch stop and no longer regulating. Then lean until the r.p.m. reaches a peak just before falling off, and finally return the throttle to the normal manifold pressure setting. Naturally the best way to lean is with the aid of an exhaust temperature (or even cylinder head temperature) gauge if one is available.

Some of the difficulties which may be encountered with variable-pitch propellers are sluggish response, hunting or surging, and improper r.p.m. limits. It is normal for response to be sluggish at low-engine r.p.m. or when the oil is still cold and does not flow freely. Persistant cases may be due to partial restrictions in the oil lines and should be investigated.

Hunting around the selected r.p.m., or sudden surges in r.p.m., followed by a return to normal speed are normally due to troubles in the governor, unless just a faulty tachometer indication, and can generally be cured by cleaning the governor and purging all air from the oil passages. Failure to reach takeoff r.p.m. during the takeoff run, or overspeeding during any flight operation require adjustment of the governor or perhaps the pitch stops on the propeller itself. These are all jobs for a mechanic.

Daily or preflight inspection of the propeller system includes a check of the general condition of the propeller and spinner, and a check for evidence of oil or grease leakage around the hub. Nicks or cracks should be brought to the attention of a mechanic and repaired only under his supervision, while leagage indicates the probable need for at least a minor propeller overhaul. A thorough inspection of the hub assembly is made at the 100-hour (or annual) inspections, and a complete teardown and refinishing by a propeller shop should occur at 500 to 1,000 hours —generally to coincide with engine overhaul.

Serious malfunctions in flight can result in the propeller going to either maximum high or low pitch, depending on the type of propeller and the nature of the malfunction. If the propeller goes to full-high pitch in a nonfeathering propeller, the r.p.m. will drop off considerably due to increased engine loading. Flight can still be maintained, but should be at somewhat reduced power to avoid damage to the engine. Feathering-type propellers have no high-pitch stop when in flight, so the propeller will go to the feathered position. This will require a shutdown of the engine.

If the propeller goes to full low pitch it will overspeed, requiring reduction in throttle and airspeed until the r.p.m. is within limits. Flight can then be maintained at reduced power and airspeed to maintain an acceptable r.p.m. In most instances on a twin an attempt should be made to feather the propeller. However, if this is impossible, flight at a sufficiently low airspeed should keep the windmilling speed acceptably low or even allow some power to be developed by the engine. McCauley recommends that propellers which have been subjected to less than 15% overspeed receive a thorough visual inspection, while those with 15% to 30% overspeed should be completely torn down for internal inspection. Propellers subjected to 30% or more overspeed should be returned to the factory for rebuilding.

For all the merits of constant-speed propellers, there are a few operational features which can cause a certain amount of distress to the unwary pilot. Primarily these have to do with the fact that one gets used to judging power and airspeed by *sound* with fixed-pitch propellers, and this extra sense is lost with constant-speed propellers. One situation occurs, for example, when changing power settings during an approach for landing. The pilot accustomed to adjusting for a slight change in sound will suddenly find that what he thought was a small power reduction actually amounted to practically shutting down the engine. There is no choice but to look at the manifold pressure whenever a power change is made. This is not really a bad idea anyway, since it allows much better power control.

The second notable difference is that the braking effect and resultant speed stability due to fixed pitch propellers is gone. If the airspeed increases from cruise, the propeller will tend to speed up also. The governor immediately corrects for this by increasing the pitch until the propeller is slowed down by the aerodynamic load again. Thus instead of acting as a brake, the engine goes merrily on developing power as usual. This fact makes IFR misadventures such as the graveyard spiral much more likely than with fixed-pitch type aircraft.

The fixed-pitch propeller tends to keep the speed from increasing too rapidly and alerts the pilot by changing r.p.m. ad therefore its sound. The constant speed propeller, on the other hand, keeps pulling and aggravating the situation and leaves the pilot completely unaware of the trouble. Experiments are being conducted with another system of control in which the pilot would set propeller pitch directly, and engine r.p.m. would automatically be controlled by a regulator on the throttle. Among other good features, this system would restore a braking effect to the propeller. ●