WIND TUNNEL

Let's look closely at those whirling blades.

By Barnaby Wainfan

As we saw last month, the simplest way to analyze propellers is by considering them as *actuator disks* that add velocity to the air as it passes through. The actuator disc is an appealingly simple theory and gives some useful results. Unfortunately, real propellers are not magic disks that impart momentum to the air. Instead, they are an assemblage of whirling blades that interact with the air in a much more complex way. The aerodynamic characteristics of the blades have a large impact on the efficiency of the propeller. We will take a look at some facets of propeller blade design, and how they affect the characteristics of the prop.

Tip Mach Number

One of the major concerns of a propeller designer is the Mach Number of the blade tips. In many cases, this is the most important factor in determining the allowable diameter of the propeller. The design rpm of the prop is set by the characteristics of the engine (and sometimes the PSRU or gearbox). With the rpm set, the tip speed of the propeller is determined by two factors, the propeller diameter, and the airspeed.

The tangential speed (speed due to the rotation of the prop) of the tip of the blade of a propeller is given by:

$$V_r = \pi DN/60 \text{ fps}$$

Where:
V_r = velocity due to rotation
D = propeller diameter in feet
N = propeller rpm

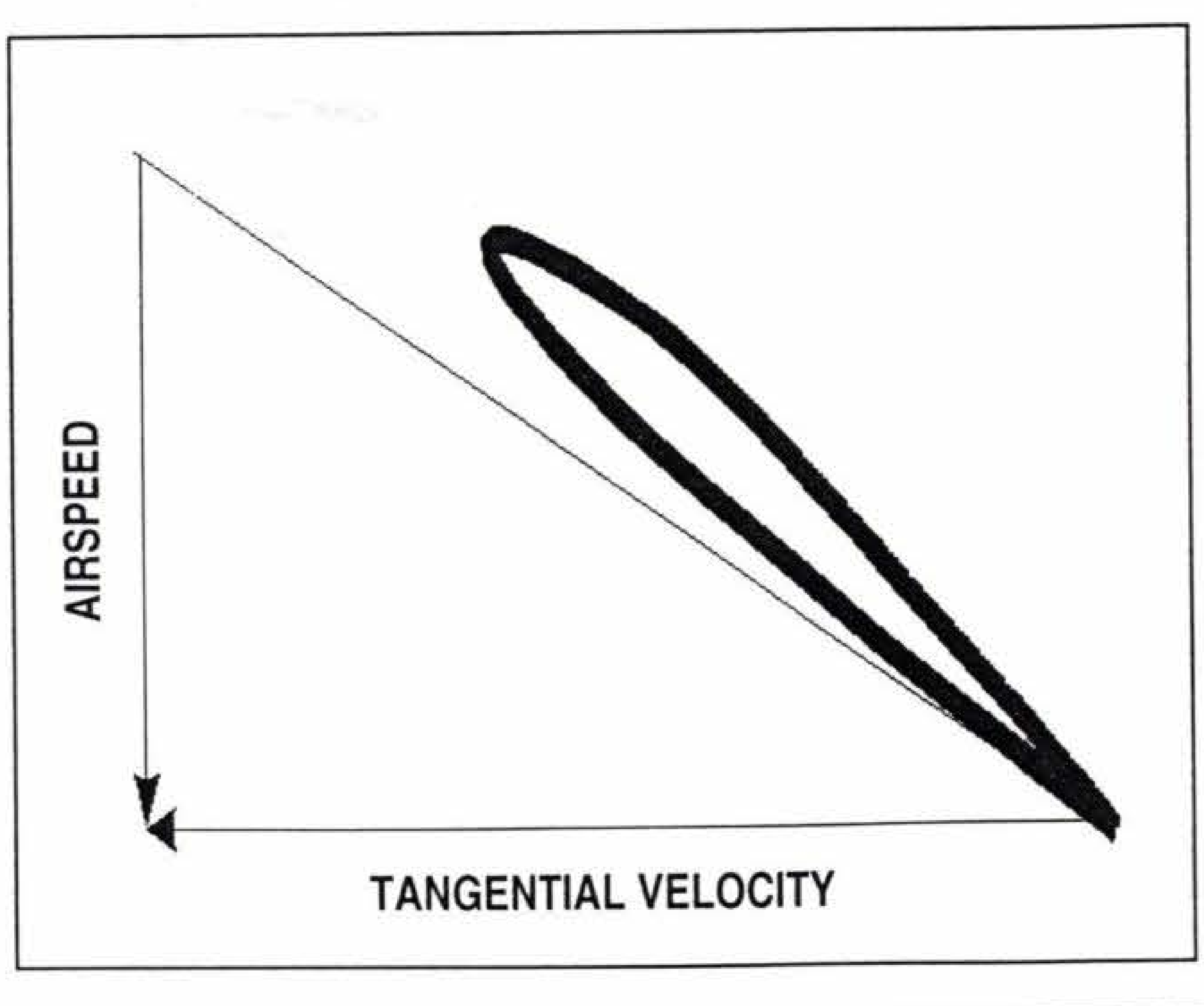
When the airspeed of the propeller blade tips approaches the speed of sound, two things happen: First, the propeller efficiency drops, and second, things get very noisy. The Mach number at which this happens varies somewhat depending on the shape of the blades and the thickness of the propeller blade airfoil near the tip. One of the primary reasons for the shift from wood to metal props was the fact that a metal prop could have thinner blades, particularly near the tips. These thinner blades could be driven to higher tip mach numbers before the propeller efficiency started to degrade. In recent years, composite props have found favor because they allow the thin blade profiles of a metal prop, but are lighter, stiffer and more fatigue-resistant than metal props.

Supersonic Props

Propellers with supersonic tips are only used in a few special cases. One such use is the Formula 1 air racing class. These airplanes are required to use direct-drive engines of a specific type, and thus the only way to get more power out of them is to turn them faster. Since the goal is pure speed, propeller efficiency is not the critical parameter. What is important is the total thrust horsepower coming from the propulsion system. This is the product of engine power times propeller efficiency. Maximum thrust horsepower is achieved at an rpm somewhat above the rpm at which propeller efficiency starts to fall off because engine power keeps increasing with rpm. The maximum occurs when the rate of propeller efficiency loss is equal to the rate of power increase. For Formula 1 airplanes this leads to blades with supersonic tips.

Propellers with blades designed to be locally supersonic were experimented with by NACA in the 1950s to study high-speed turboprop concepts that at the time were seen as superior to jets for long-range missions. These props had relatively small diameters, with wide-chord, extremely thin blades. While the results of these propeller experiments were encouraging, the state of the art in jet engine design advanced quickly enough that the supersonic-propeller turboprop approach was bypassed in favor of the turbojet, and later the turbofan. This was probably a good thing, because the supersonic-blade propellers were appallingly noisy. Republic Aviation built a pair of prototypes of a turboprop-powered version of the F-84, the F-84H for the U.S. Air Force. These airplanes were so loud that the sound of the prop was above the threshold of pain 100 yards away when they were run up on the ground. The loud props caused the F-84H to be tagged with the unofficial name "Thunderscreech." The program was not a success and was quickly canceled. One of the two prototypes survived and is now doing planesickle duty at an airport gate in Bakersfield, California.

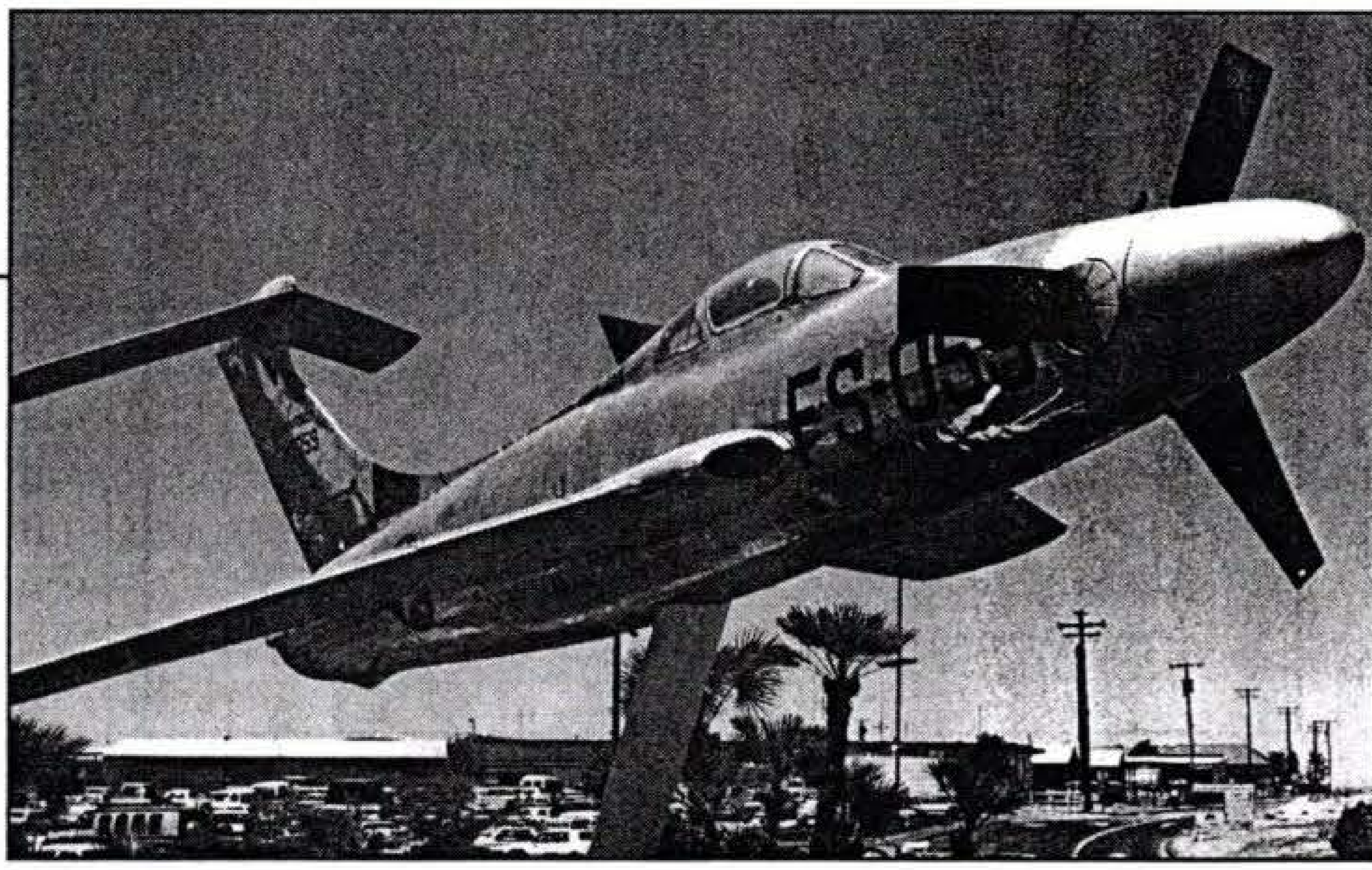
Figure 1. The angle at which the air arrives at each element of the propeller blade depends on the airspeed, the distance from the hub, and the rate of rotation of the propeller.



Blade Inflow Angle

As the propeller moves through the air, each point on the blade follows a helical path. The angle of this helix is determined by the rotational speed of the propeller, the forward airspeed, and the radial distance from the axis of rotation. The angle is different at every radial station on the blade.

Figure 1 shows how the local helix angle is determined. The blade element has a tangential velocity (velocity due to propeller rotation) that is normal to the propeller axis of rotation. The forward airspeed of the airplane produces a velocity component that is parallel to the propeller shaft. The local helix angle is determined by the relative magnitude of the axial velocity (due to airspeed) and the tangential velocity (due to rotation).



The very-experimental Republican F-84H had a supersonic prop. The sound level was above the threshold of pain 100 yards away.

The propeller blade element sees an incoming airflow approaching at the local helix angle. Note that the lift generated by the propeller blade element is normal to the incoming flow rather than parallel to the propeller axis of rotation. The helix angle is always 90° at the center of the prop hub, where the tangential velocity is zero. As we move outboard on the blade, the angle decreases.

The Advance Ratio

The helix angle described by any point on the blade is determined the ratio of the tangential velocity and the airspeed. This is independent of the absolute value of these two speeds. As long as the ratio is the same, the angle is the same. Because of this, engineers have defined a quantity called the *advance ratio* of a propeller, which is used in calculations of propeller characteristics. It is also a fundamental parameter against which experimental propeller performance data are plotted. For reasons undoubtedly long lost in history, the symbol for the advance ratio is a capital "J".

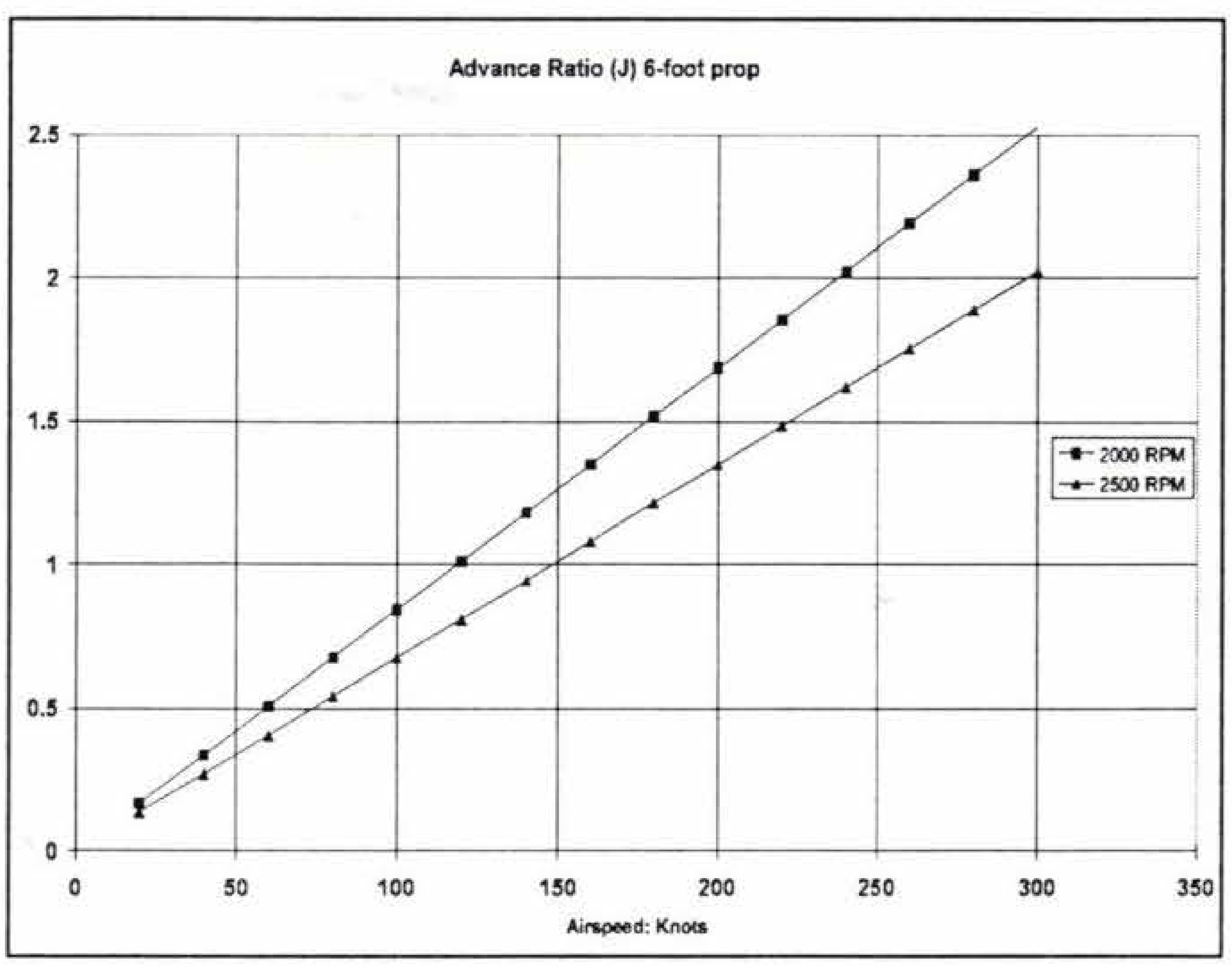
The advance ratio (J) is given by:

$$J = V/(nD)$$

Where:
V = the airspeed in feet per second
D = the propeller diameter in feet
n = the propeller rotation rate in revolutions per second

As its name implies, the advance ratio is proportional to the ratio between the tangential speed of the propeller blade tip and the forward speed of the airplane. For a given propeller diameter and rotation rate, the advance ratio is proportional to the airspeed. Figure 2 shows the value of advance ratio for a 6-foot (72-inch) diameter propeller as a function of airspeed for two values of rpm. Note that for the low airspeeds typical of ultralights (50 knots) the advance ratio is less that 0.5, while for fast airplanes it is typically 1.0 or above.

Figure 2. Advanced ratio vs. airspeed for two different rpm values.



Inflow Angle and Blade Twist

One reason advance ratio is an important consideration when designing or selecting a propeller is that both the magnitude and the distribution of inflow angles along the blade change with advance ratio. Figure 3 shows the local helix angles over the blade plotted for a range of advance ratios.

The first thing we note looking at the curves is that as advance ratio increases, the whole curve moves up, indicating a steeper helix angle for the propeller. This is not surprising. It says that as airspeed increases (higher advance ratio), we need a higher-pitch propeller.

The curves also illustrate a second more subtle phenomenon. For a propeller to operate efficiently it is desirable to have the majority of the blade at the same angle of attack relative to the local incident airflow. This causes most of the blade to be operating at the same lift coefficient. Ideally, the whole blade is operating at the lift coefficient at which the blade airfoil achieves its maximum lift-to-drag ratio. We achieve this uniform angle of attack distribution by twisting the propeller blades properly.

Look at the bottom curve, which is for a very low advance ratio. Notice that, although the inflow angle is very high at the root, it falls off very rapidly, and by 20% of the radius it is down to just under 10°. Over the remaining 80% of the blade length, the inflow angle drops to about 2°. If we wanted to keep all sections on the blade of this propeller at the same angle of attack relative to the local incident airflow, the blade would need about 8° of twist from the 20% radial station outboard.

Inboard of 20% we would need a lot of twist, and the blade should theoretically have an incidence of 90° at the root. Fortunately, the inner 10-20% of a propeller blade is usually either part of the hub or inside the spinner.

Now let's turn our attention to the top curve on Figure 3. This curve is for a propeller operating at a much higher advance ratio than the previous example. At 20% of radius out from the center, the local flow angle is about 70°. At the tip, it has dropped to about 28°. To achieve uniform blade-element angle of attack, this prop would need about 42° of twist between the 20% radius station and the tip. This is quite a difference from the 8° needed for the very low advance ratio prop.

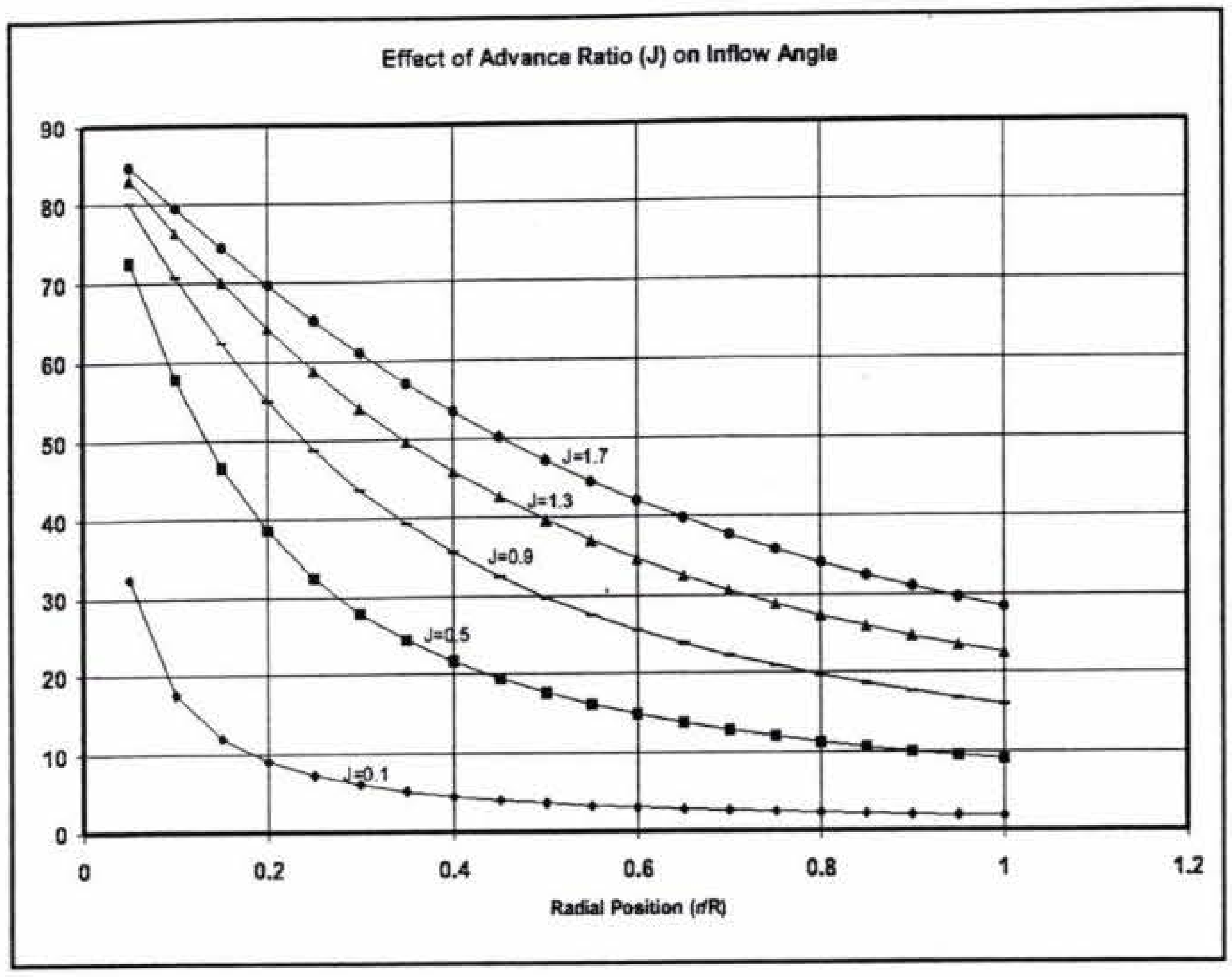


Figure 3 shows the local helix angles over the blade plotted for a range of advance ratios.

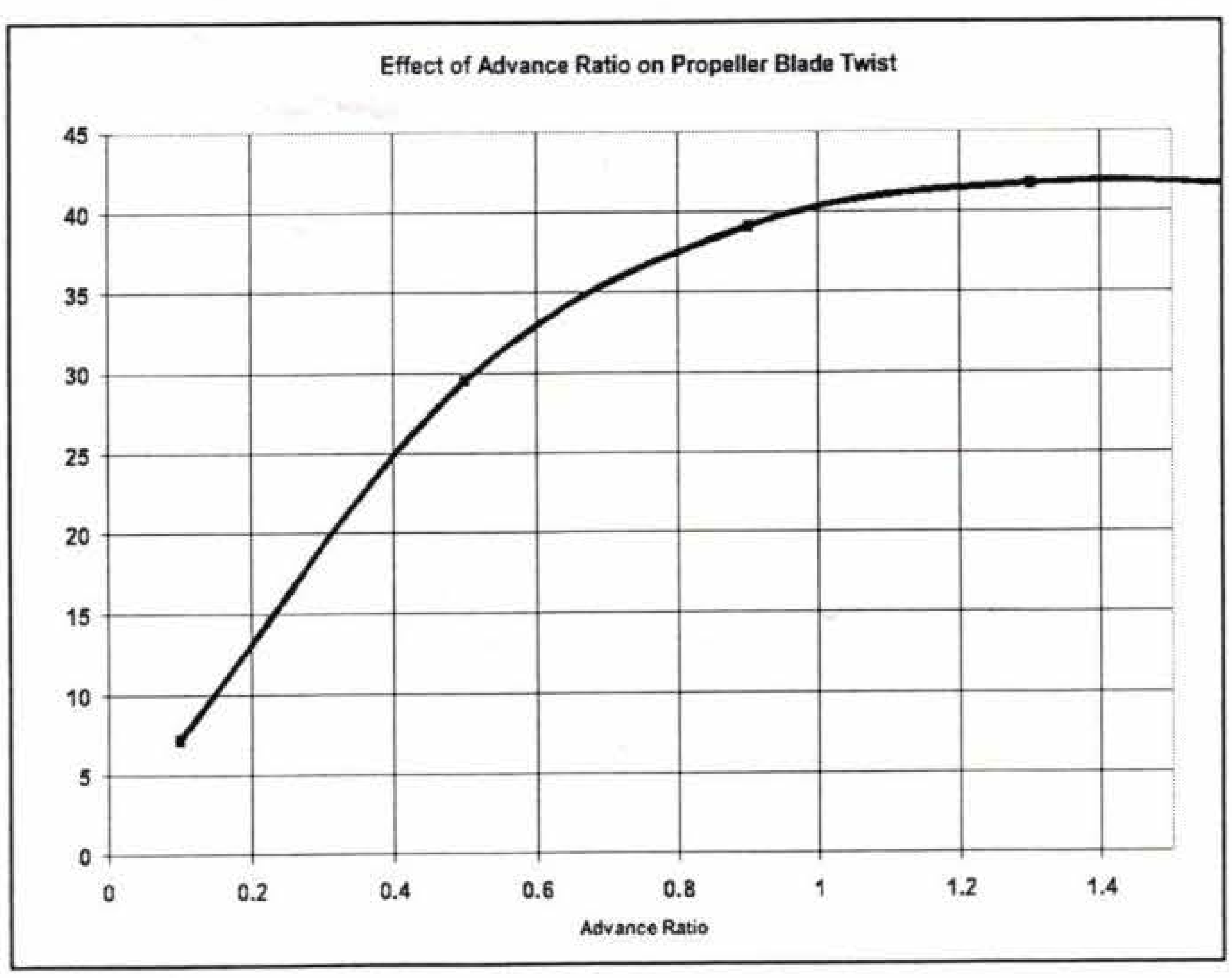
Figure 4 shows the twist required to achieve uniform blade angle of attack as a function of advance ratio. If we compare an ultralight-like value of 0.3 for J to the 1.0 to 1.5 typical of faster airplanes, we can see that there is a dramatic difference in the twist distribution required for an efficient propeller. If the twist in the propeller blades does not match the advance ratio at which it is flying, part of the blade will be at a non-optimum angle of attack.

Consider a ground-adjustable or controllable-pitch propeller designed to fly at low speed (low advance ratio). Suppose we decided to use this propeller on an airplane that flies faster than the design speed of the prop. To get thrust out of the propeller, we add pitch by rotating the whole blades. The blades are twisted for low speeds and do not have enough twist for high speeds. After the pitch change, the tips will have too high an angle of attack and the roots will be at too low an angle of attack.

This situation is very inefficient for two reasons. The inner portions of the blades might actually be operating at negative angle of attack, producing negative thrust at high speed. Even if they are not, they are not producing their fair share of thrust. They are still producing drag that opposes the rotation of the propeller and soaks up engine power without doing anything useful.

During early flight tests on my Facetmobile, I was using a propeller designed for ultralights. It pulled very well during the takeoff roll and initial climb, but cruise performance was disappointing. After a few flights, I noticed that I was getting bug strikes on the forward face of the inner third of the propeller blades. Obviously, not an efficient situation.

Figure 4. The twist required to achieve uniform blade angle of attack as a function of advance ratio.



This does not mean that the propeller was a bad design. it was designed to produce a lot of thrust at low airspeed. It did this well. Unfortunately for me it was not well suited to the higher-than-ultralight cruise speed of the Facetmobile.

At the other end of the blade, the tips are too highly loaded, and are operating at a lift coefficient that is higher than the best L/D lift coefficient of the blade airfoil. Once again, too much blade drag is being paid for too little thrust.

One important lesson comes from this. It is common for propeller manufacturers, particularly those who sell to the ultralight community, to advertise how much static thrust their prop produces. A static propeller is at the lowest of advance ratios: zero. Static thrust might be a valid figure of merit for propellers for very slow-flying airplanes, but it is essentially meaningless as a measure of how good the prop will be on a faster-flying machine.

If the situation is reversed, and the blade is twisted for higher advance ratio, but de-pitched and flown slowly, once again we find some inefficiency. The inner portion of the blade is at too high an angle of attack, and the tip is at a lower-than-optimum angle of attack. The loss of efficiency is less severe than the case we just discussed. The outer portion of the blade will be closer to its optimum angle of attack, and while the inner portion of the blade is operating at too high an angle of attack, it is at least producing thrust. For a variable-pitch propeller, it is much better to twist the blade for optimum performance at cruise and accept the loss of efficiency at low speed than to fail to put sufficient twist in the blades.

Blade Planform

If we look at the airspeed of the blades as a function of the distance from the hub, we can see immediately that an efficient propeller will have a significant amount of taper in the blades. The tangential component of the velocity of a blade element increases linearly as we go outboard on the blade. The dynamic pressure of the air increases as velocity squared. As we saw earlier, it is efficient to have a constant lift coefficient along the blades. If the blades had a constant chord, the lift on the blades would increase roughly as the square of the distance from the hub. This would make the prop excessively tip loaded. By tapering the blade, we achieve a more uniform thrust loading along the blade.

The ideal loading on a propeller changes with advance ratio. So does the variation of blade element airspeed along the blade. Accordingly, there is no single *ideal* propeller blade planform. Each propeller must be designed to match a specific advance ratio and power input.

At low advance ratios, the tangential velocity dominates. This causes a large variation in airspeed over the length of the blade. Props designed for low advance ratios accordingly tend to have very highly tapered blades.

At higher advance ratios, the forward velocity becomes more significant. This reduces the variation of airspeed over the length of the blade and makes the optimum planform somewhat less tapered. The most extreme example of this is the supersonic-blade prop used on "Thunderscreech," which had essentially constant-chord blades and was designed to operate at an extremely high advance ratio.

There are now computer programs in existence that can define an optimum distribution of blade area and twist for a propeller operating at any given advance ratio and power or thrust. Even with these tools available, propeller designers continue to explore the effects of blade sweep, blade airfoil and tip design on propeller performance, in search of that last extra bit of efficiency. **KP**

Aerodynamic questions of a general nature should be addressed to "Wind Tunnel" c/o KITPLANES, 1000 Quail Street, Suite 190, Newport Beach, CA 92660.