Propeller Performance Factors -

Basic Information to Help Select the Correct Propeller

The performance of a propeller in flight involves several complex subjects, and the high performance propellers we have available today are the product of a huge amount of engineering, development, testing, and (unfortunately) a few mistakes. The selection of an appropriate propeller for a new aircraft should not be done without considering several factors which characterize the performance of a propeller. The following sections (EFFICIENCY, TIP SPEED, and PERFORMANCE MAPS) present a few basics regarding propeller performance.

EFFICIENCY

The purpose of a propeller is to convert power (delivered by a rotating shaft) into thrust. It does that by accelerating a large mass of air to a higher velocity. The effectiveness with which a propeller performs this conversion is known as "efficiency".

As you already know, a propeller blade is a sophisticated whirling airfoil. At a constant RPM and aircraft true airspeed, the speed of the air over any portion of the airfoil varies with the distance from the center of rotation. The maximum velocity occurs at the point of maximum thickness out near the tip.

Therefore, in an effort to provide an ideal angle of attack all along the blade, the blade has a "twist" to it which varies the pitch angle of the blade from root to tip. The pitch angle of a blade (β) is typically the angle measured at 75% of the radial distance from the center of rotation to the prop tip.

As aircraft velocity increases, the angle of attack seen by the prop blade of a fixed-pitch prop will decrease. That effect limits the maximum efficiency of a fixed pitch prop to a single airspeed at a given RPM, as shown by the following plot (ref-4:13:149) of efficiency at different blade pitch angles (β) shows.

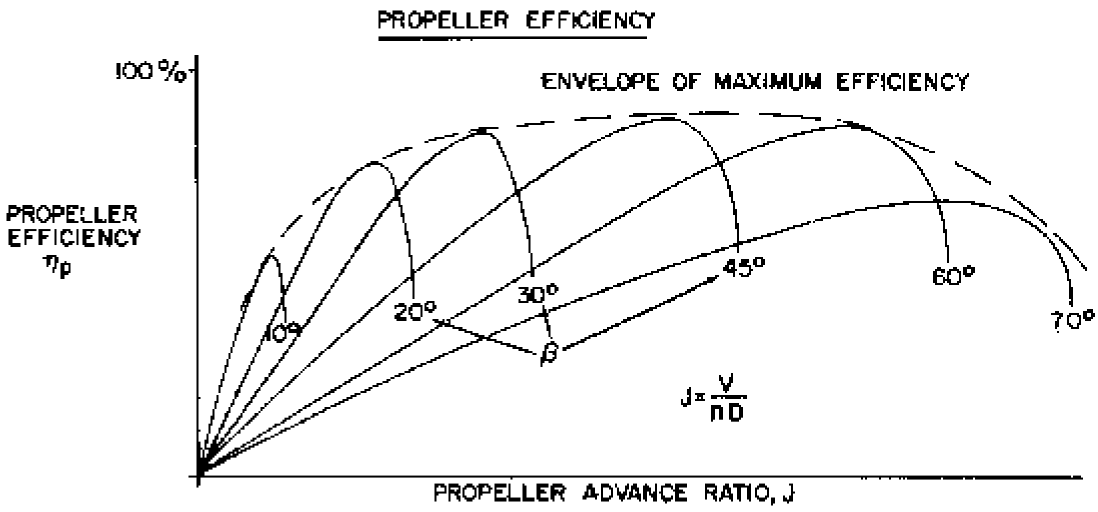

Figure 1

The curves in Figure 1 suggest that if the blade pitch could be varied in flight, the prop efficiency could be very high for a wide range of operating conditions. Therefore, many propellers contain a mechanism in the hub to change the overall pitch of the blades in response to a servo command from a control system. That control system is typically a propeller governor, which maintains prop RPM at a pilot-set value (within certain limits) regardless of aircraft speed or engine power setting.

Propeller efficiency is defined as:

eff = "K" * Thrust * Speed / Power

(where "K" is a constant to account for units).

If the system of units is Pounds (thrust), Horsepower (power) and Knots True Airspeed (KTAS), then the equation becomes:

eff = (Thrust * KTAS) / (HP * 326)

(if you prefer MPH instead of Knots, use 375 instead of 326)

The equation for efficiency has other useful forms. Rearranging the terms, the equation for the thrust produced at a known airspeed, engine power, and prop efficiency is:

Thrust = (HP * eff * 326) / KTAS

To find the HP required to produce a known thrust at a known airspeed and prop efficiency:

HP = (Thrust * KTAS) / (326 * eff)

To find the speed which can be reached with a known engine HP, prop efficiency and airframe drag (thrust = drag in steady state level flight):

KTAS = (HP * eff * 326) / Drag

It is clear from the relationship between power, thrust and speed, that if power and propeller efficiency are held constant, then propeller thrust decreases as true airspeed increases. Add to that the fact that aerodynamic drag increases with the square of speed, and it becomes clear why it takes 8 times the power to double the airspeed ($8 = 2^3$) of a given airframe (oversimplified to make the point).

Figure 2 shows a plot of the thrust generated by a particular (variable pitch) propeller as a function of the airspeed (15 through 240 MPH) and power applied to it (250 through 500 HP).

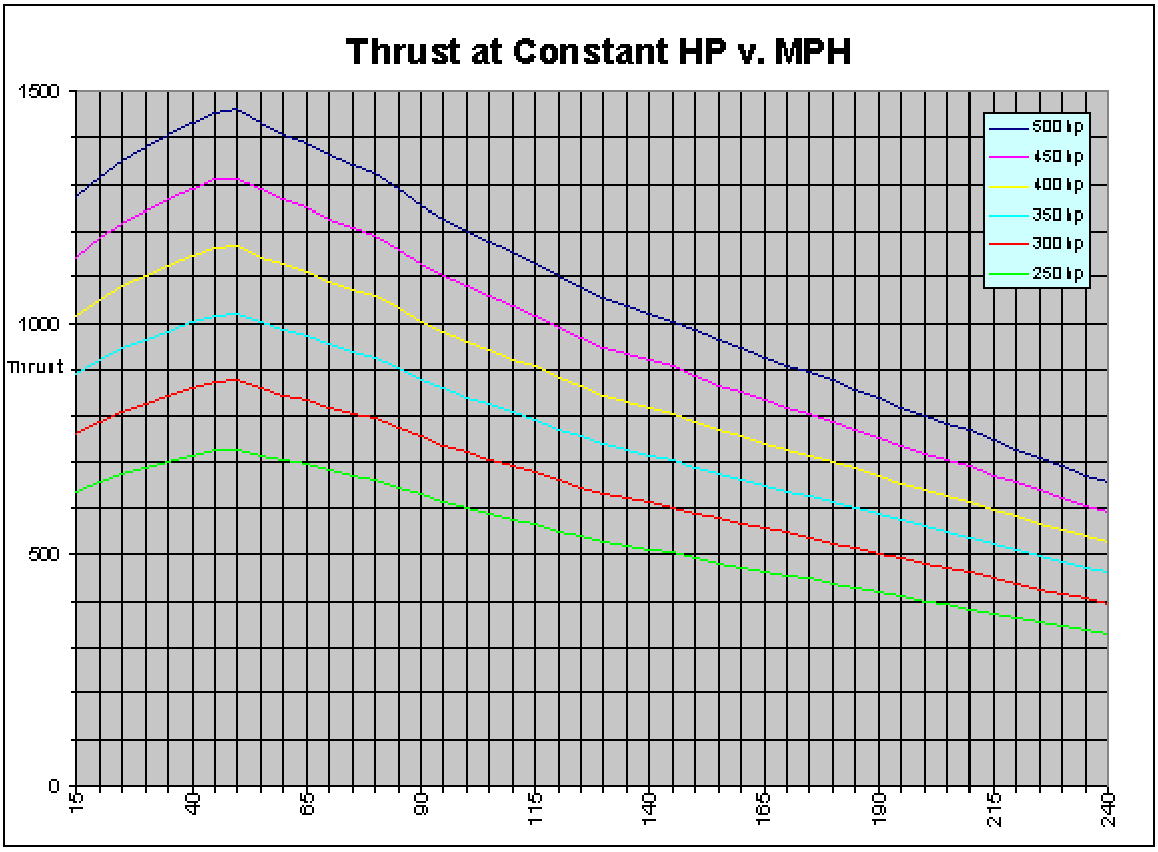

Figure 2

In case you were wondering, the hump in those curves is due to the fact that at low airspeeds, prop efficiency is very low. As airspeed increases, so does efficiency, quickly at first, then more slowly, up to it's max (about 85-87%).

In general, the larger the prop diameter, the more efficient it will be. The following three equations (ref-4:9:219) provide an estimate of the recommended prop diameters (inches) as a function of the horsepower available to the prop. ("Fourth root" is the square root of the square root.)

Two-blade: d = 22 x fourth root of (HP)
Three-blade: d = 18 x fourth root of (HP)
Three-blade (agricultural application): d = 20 x fourth root of (HP)

However, the maximum useful prop diameter will be limited by the speed of the prop tip.

TIP SPEED

Anytime the aircraft is in motion (and the propeller is turning, of course) the path of the tip of a prop blade through the air is a helix, and therefore, it's velocity (the "tip speed") is the vector sum of the rotational velocity plus the translational velocity, or the helical tip velocity (explained in detail below).

Maximum helical tip velocity is an important parameter for propeller selection. In the absence of specific data from the prop manufacturer, it is safe to assume that (a) the maximum prop efficiency will be about 87% (for any metal prop a non-governmental agency can afford), and (b) that the prop efficiency begins to decrease dramatically when the prop is operated at a helical tip velocity in excess of 0.85 Mach. That occurs because the local air velocity over the surface of the prop (near the point of maximum airfoil thickness) will reach Mach 1, and create a shock wave, separating the flow and dissipating prop energy.

That phenomenon is very easy to spot in a high speed aircraft which has the capacity to run the prop too fast. Here is an example. A few years ago, I was flying a Glasair-3 to an airshow. I was cruising at 13,000 feet, 2400 RPM, wide open throttle. I was running a bit behind schedule, so in pursuit of a few more knots, I decided to operate at max power (2700 RPM, WOT). It was something of a surprise when I lost about 15 knots of airspeed. I set the RPM back to 2400, and regained the lost 15 knots. Later I did the calculations to verify that the loss was due to the sudden loss of efficiency. It was.

It is actually quite simple to do the arithmetic necessary to determine the tip Mach of a prop at a given RPM and true airspeed. First, calculate the helical tip velocity components.

The rotational velocity is the diameter of the prop times the RPM times a conversion factor. Again using KTAS as the unit of speed, the rotational velocity in feet per second is:

Vr (ft / sec) = RPM * Prop Diameter (inches) * 3.1416 / (12 * 60),   or

Vr (ft / sec) = RPM * Prop Diameter (inches) / 229.2

The translational velocity is simply the aircraft TAS expressed in feet per second, or:

Vt (ft / sec) = KTAS * 6076 / 3600   or Vt = KTAS * 1.688

With the rotational and translational speed (in the same units, of course) you can easily calculate the helical tip speed:

Vht = square root ($Vr^2 + Vt^2$)

Next, calculate the speed of sound (Mach 1.0). The speed of sound in air varies with the square root of absolute temperature ONLY, as defined by the following equation:

Vs = square root (k*g*R*T)

where k, g and R are constants (1.4, 32.17 and 53.34 for air)
and T is the absolute temperature (°F + 460) of the surrounding air.

So, if you are at 13,000 feet on a **standard day**, the air temperature is 12.71 °F and the speed of sound (in feet per second) is:

Vs1 = square root (1.4 * 32.17 * 53.34 * (460 + 12.71))
Vs1 = 49.013 * square root (472.71) = 1065.6 ft / sec.

The Mach number of a given speed is simply:

M = speed / Vs1

Putting it all together in a specific example, suppose you are flying at 13,000 feet on a standard day at a true airspeed of 240 knots and an 84-inch prop turning at 2700 RPM. Here is how to calculate your prop-tip Mach (using the simple equations above):

Vr = 2700 * 84 / 229.2 = 989.5
Vt = 240 * 1.688 = 405.1
Vht = square root (405.1^2 + 989.5^2) = 1069.2 feet per second
Tip Mach = 1069.2 / 1065.6 = 1.034

See why the Glasair slowed down?

Now, to calculate the RPM at which a known tip mach occurs on your propeller, perform a bit of simple algebra on those four equations (Vr, Vt, Vs1 and M) to solve for RPM, given Prop Diameter, TAS, and outside air temperature.

(Instead of doing the calculations by hand, it is very convenient to put the equations into an Excel spreadsheet and let your computer do the arithmetic. The computer is much faster at it that you are.)

PERFORMANCE MAPS

Propeller performance maps are 3-dimensional tables which list the efficiency of a propeller at various combinations of advance ratio and power loading for various altitude conditions. If you are fortunate to have access to a map for your prop, you can determine the operating efficiency accurately for most every condition (as long as map data represent the actual performance of the prop, which is not always the case !).

In order to use a performance map, you will need to calculate the advance ratio and power loading.

Advance Ratio (J) = TAS / (N * D) and

Power Loading (Cp) = (Prop HP * 550) / (air density * N^3 * D^5)

where
TAS is true airspeed in feet-per-second;
N is prop speed in Revs-per-second;

D is prop diameter in feet;
air density in is slugs-per-cubic foot (sea level = 0.002376)

Source:

http://www.epi-eng.com/propeller_technology/selecting_a_propeller.htm