BIG ENGINE, Little Airplane

Calculate the power required for best performance.

By Bill Welch

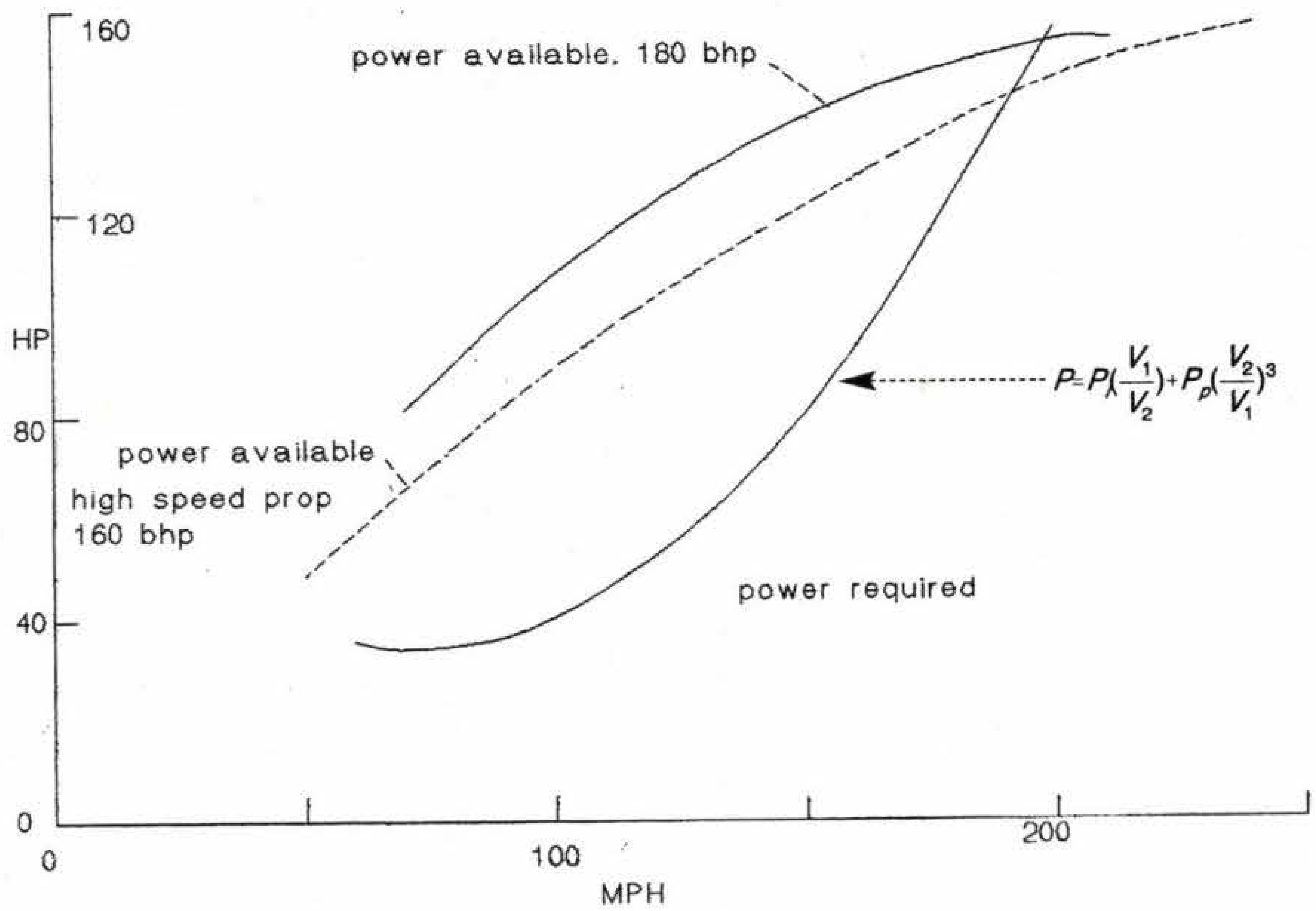

Figure 1

To go faster, you apply more power, right? Yes, but the real question is how much? All pilots have been exposed to the classic power required and power available curves, but few have analyzed the relationships on which they are based. Consequently, many people who have installed more power in airplanes have been surprised and disappointed in the result.

Aerodynamic drag, if all else is unchanged, varies with the square of velocity, but power is the rate of energy usage. Since force is related to the square of speed, and power is a rate, the drag is multiplied by the speed to obtain power. This means power is a function of speed cubed (V_A). This doesn't mean much when airspeed is low, but in the range of top speeds it becomes a formidable factor.

How It Works

The power-required curve in Figure 1 is for a popular kit airplane normally equipped with a 160-bhp (brake-measured horsepower) engine. This plot is thrust power after propeller efficiency is applied. Notice how steep the curve is at the high-speed area on the right. At any speed between the minimum and maximum, this curve is almost exclusively a function of speed cubed, because the induced drag diminishes rapidly.

The power required really consists of two distinct parts: the *induced power* and the *parasite power.* W. S. Diehl, in his "Engineering Aerodynamics," noted that if we know the two elements of power required at only one speed, we can predict them for other speeds to construct the whole curve with sufficient accuracy for many purposes. Induced drag and power are due to the production of lift, depending only on span loading and speed. All else is called parasite drag and includes wing profile drag, fuselage drag, engine cooling drag and so on. Although not precise, as it does not account for variation of parasite drag coefficient with angle of attack, this is adequate for most comparisons.

The general performance is defined by the power available curve on the diagram. The propeller is assumed to be selected for maximum speed, which is usually also nearly optimum for cruising at 75% power. The next more powerful engine available produces 180 bhp, and adding another power-available curve for that engine, we see the very small resulting increase in the maximum speed. The difference amounts to $(V_2/V_1) = (P_2/P_1)^{1/3}$, which in this case

ILLUSTRATIONS: BILL WELCH

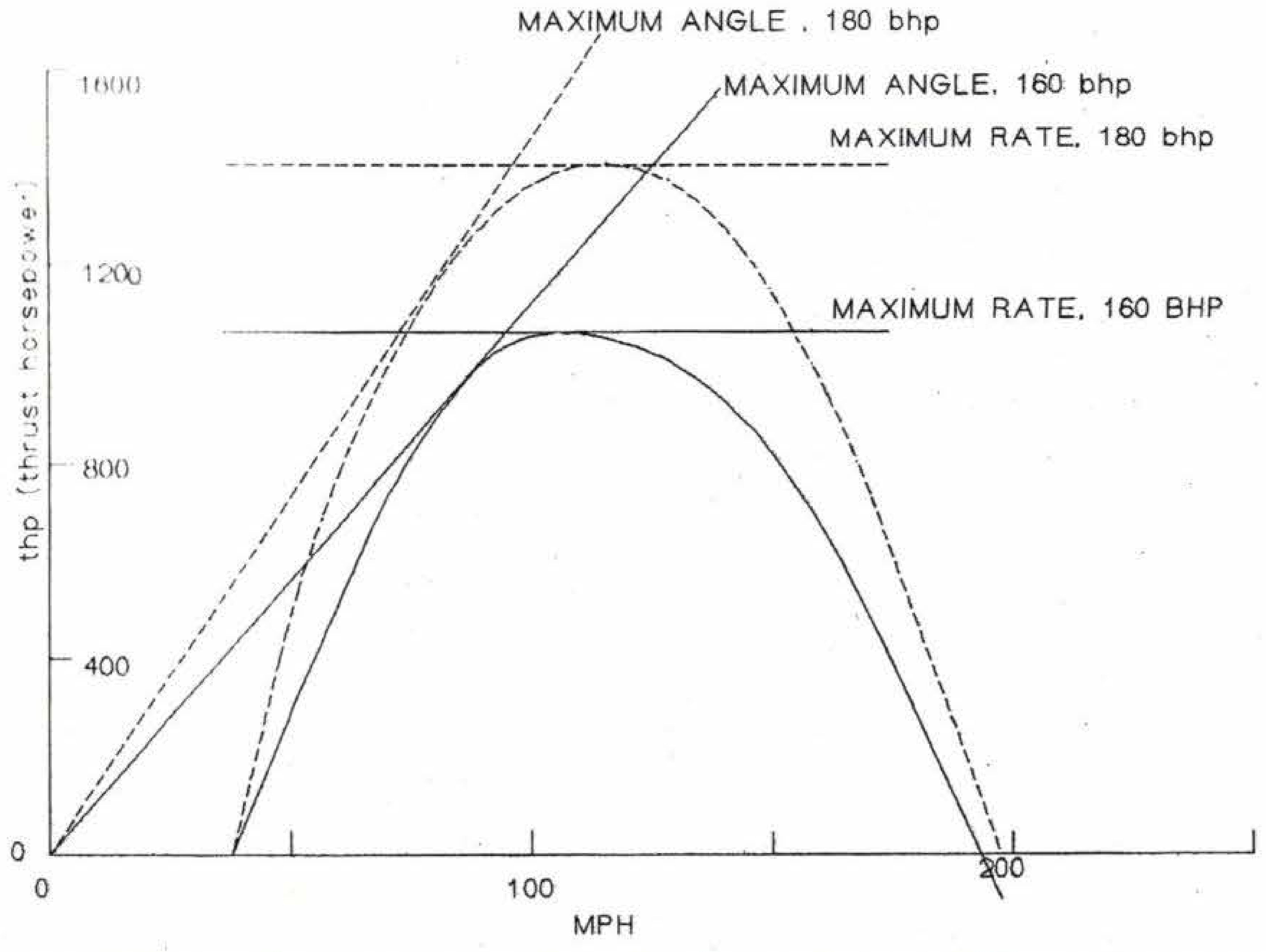

Figure 2

is only a 4% gain in speed for a 12.5% increase in power.

Adding one more line to Figure 1, we can learn something about efficiency and range. Starting from the origin, a line tangent to the power-required curve shows where the least energy is needed to move the airplane, at about 100 mph in this case. At this speed the airplane can fly the farthest for a given amount of fuel or glide the farthest without power. Fuel consumption at different settings may vary it a little, but this is close to the optimum range speed. The lowest point on the curve, the absolute least power to fly, indicates the maximum endurance speed of about 70 mph.

The two power-available curves also tell us something else about the change with increased power. The difference between power needed for level flight and what is available at any airspeed is the portion you can use for climbing. This difference varies with airspeed, and maximum shows the best rate of climb speed. With 160 bhp, the best climb is near 110 mph, and with 180 bhp, it's about 115 mph.

Climb Rates

The best climb rate means the quickest climb to cruising altitude. On takeoff, however, you may be more anxious about the best angle of climb to clear the inevitable trees or power lines at the end of the field. The most favorable airspeed for angle of climb can be roughly estimated, but the more accurate way is to measure the spread between the power curves. By plotting this difference as a function of speed, you can locate the best rate and best angle speeds directly.

By drawing a line from the origin of the plot to the rate of climb curve (Figure 2), you identify the best angle of climb and the airspeed at which this occurs. This is at approximately 80 mph with the larger engine, and it's at 85 mph with the smaller engine. Converting the numbers to the same units, the angle is nearly 30% better with the higher power, about 17 feet per hundred compared to 13. The rate of climb has increased from about 1140 fpm to about 1540, a 35% gain for the power increase of 12.5%. This is where the improvement shows up!

Plotting the performance curves of an airplane provides the designer and pilot with a tool to understand what the airplane can do and how to achieve the best performance with it. Although the figures shown started with some basic test data for a particular model, the numbers have been rounded off for illustrative convenience and provide representative plots that are not to be taken literally for any one airplane or model.

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Calculating Power

For those who wish to do their own performance estimates, here is a good tip. The best method of calculating power requirements is to compute each contribution to the total drag separately.

The manner in which cooling air and engine exhaust are discharged can be good or bad for performance. If engine baffling is poor, more pressure differential is needed to move enough cooling air through the cylinder fins and oil cooler. When an inlet or outlet is in a bad location, obtaining that pressure difference will cause more drag than if the locations are well chosen.

Giving that a little thought, you realize the pressures on an aircraft, and surface pressure surfaces vary wildly. Taking advantage of them is not difficult, you just have to pay attention and look at typical pressure distributions. Better yet, measure some pressures on the particular aircraft involved. A water manometer is simple to rig and safe to use. Discharging the flow as nearly as possible parallel to the external flow is best, and if you can match the velocities with proper outlet sizing, you have the best possible conditions.

For an oil cooler or a radiator,

don't aim a concentrated stream of air at the core. Use a plenum chamber ahead of the unit so the velocity is as uniform as possible through the core. This arrangement takes the least total flow and causes the least drag. Merely expanding a duct does not work unless the expansion is so gradual that the flow remains attached to the diffuser walls. There is twice as much energy in the cooling air and exhaust as is delivered to the propeller, so it is even possible to recover some useful propulsive thrust with clever design. The P-51 demonstrated this principle in the early 1940s with an outlet area properly matched to the heat to be dissipated and external flow.

Choose the Right Prop

Once you are satisfied the engine is delivering as much power as it should and cooling drag has been held to a minimum, it's time to optimize the propeller design for the desired result. Again, if speed is the object, the propeller can be fine-tuned for maximum airspeed at the maximum propeller rpm. This is not a simple task, and you need either a good propeller designer to advise you or one of the available propeller specification computer programs to find the right combination of diameter, pitch, solidity and number of blades.

If takeoff and climb performance is your game, the propeller selection must be biased to favor these segments of a flight. However, it would penalize the plane in cruise and limit maximum speed to avoid overspeeding the engine unless propeller pitch is controllable.

Diameter is constrained by tip speed, which can impose a real penalty if it's excessive. The general principle applies: It takes diameter to have large thrust at low speeds. At high speeds, large diameter can hurt, and it is not needed for efficiency because ample mass flow through the system is inherently available at high airspeeds.

Each drag element has its own characteristic drag coefficient. Landing gears are different from fuselages or tail surfaces and may act differently with angle of attack. When changes are made in design or construction details, the various elements can be accounted for without affecting other components of the total.

Induced drag has been commonly misunderstood because of an old and misleading term: *span efficiency.* It's a mistaken application of W.B. Oswald's *airplane efficiency,* which he used in a 1932 NACA report to simplify calculations by means of a *virtual span* before personal computers made the bookkeeping easy. It merely hides part of the parasite drag, which happens to vary with speed roughly as the induced drag does. The span efficiency factors with

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real physical meaning are induced drag corrections for planform and tip shape, which can be found in the first chapter of Abbott and von Doenhoff's, "Theory of Wing Sections." The difference from the ideal induced drag is usually quite small.

Almost any aerodynamics textbook can lead you through the process of performance estimation. The trick is to remember that airplanes are usually less than perfect, and numbers must be used with some judgment. Better to be pleasantly surprised with conservative performance estimates than disappointed when optimistic estimates aren't realized in flight. **KP**

Bill Welch died in February 1999. His widow, Virginia, has allowed us to present his unpublished articles.