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Technical Counselor Note #5
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Aircraft Performance – Chapter #1 – How Power affects Aircraft Performance

What makes airplanes fly fast? Most folks will say lots of horsepower and low drag, and they are right. The next question though, takes a little more thinking to answer, and that is: How much does my speed increase for a specific increase in horsepower or decrease in drag? In this Tech Note, we will explain in simple terms how to answer the question of how changes in horsepower affect airspeed and climb rate. In a future note, we will discuss how changes in drag affect aircraft speed.

So, your airplane's maximum speed is known, and you know how much horsepower your engine is rated for, and you want to know if you put a larger engine up front, how much faster it is going to go. This is not too tough to estimate if you are willing to do a little bit of algebra. So here are the steps we need to go through.

1) We need to know the rated horsepower of the current engine.
2) We need to know the actual horsepower that is being generated.
3) We need an accurate measurement of what our true airspeed is with the actual horsepower being generated.
4) We can then estimate the increase in true airspeed with an increase in horsepower.

How about a nice little turboprop for your experimental?

Determining horsepower

Lets first figure out how much horsepower our engine is making. It helps understand what the unit of horsepower means. Horsepower is a measure of how much work is accomplished in a given time period and was defined by James Watt. You see, Jim was trying to sell steam engines to coal mine owners to lift the coal out of their mines. The owners were using horses to accomplish this task at the time, so James needed a way to compare his engines to the number of horses required to do the same job. Jim determined that a horse could turn a mill wheel 144 times in an hour (or 2.4 times a minute). The wheel was 12 feet in radius, therefore the horse travelled 2.4 2π 12 feet in one minute. Watt judged that the horse could pull with a force of 180 pounds. So if,

Power = work/time,

and,

Work = force *distance,

then,

Work = (2.4 * 2 *3.14156 * 12 (ft) *180 (lbs)/ 1(min)=32,572 (ft-lbs/min)

Jim rounded the unit of horsepower up to 33,000 (ft-lbs/min) and rated his steam engines based on this number. It has been used ever since. If you would like to read more on horsepower, here is an interesting reference:

http://www.pumaracing.co.uk/POWER1.htm

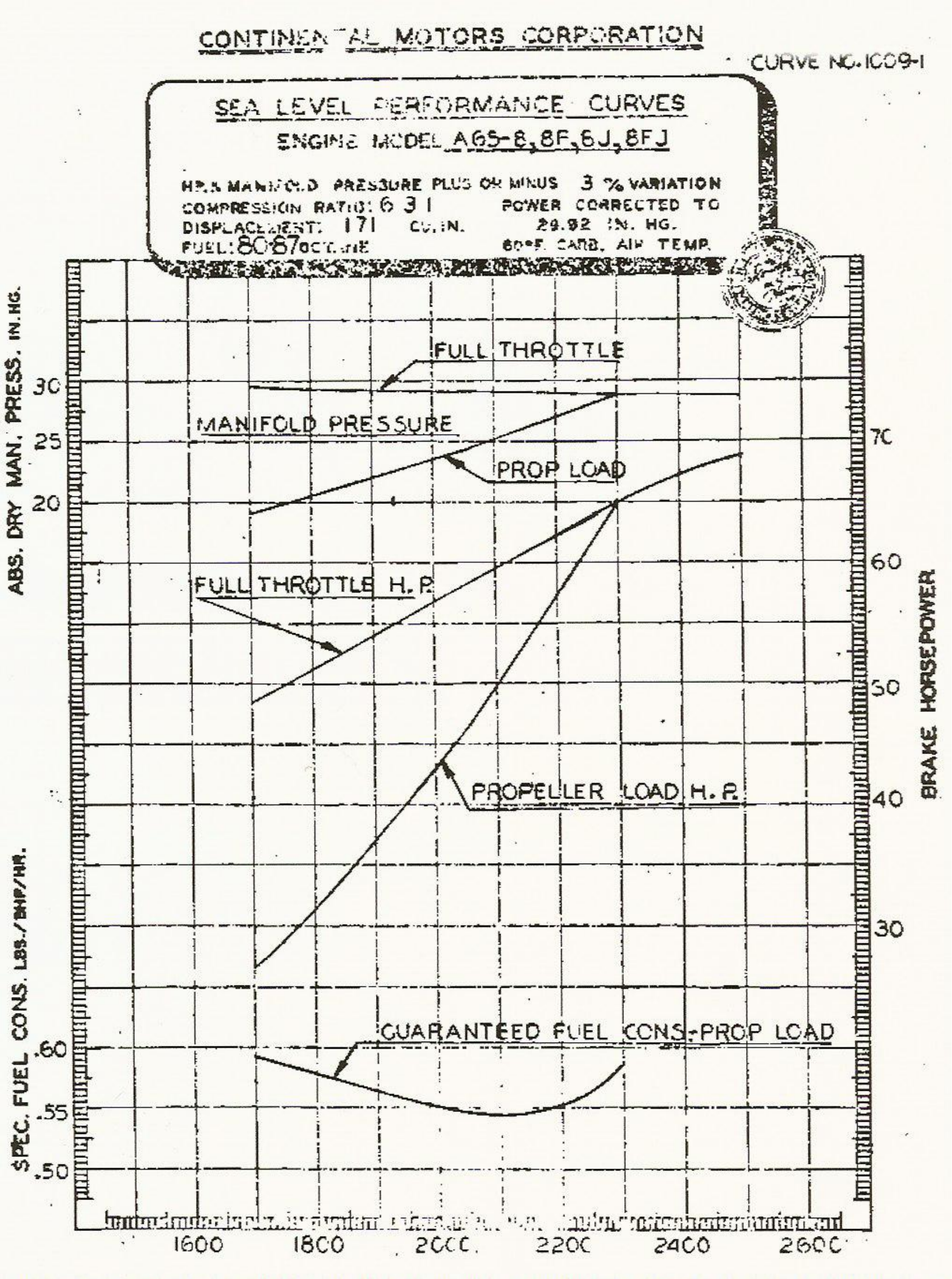
Horsepower can also be calculated using the following formula:

Horsepower = Torque (ft-lbs)*RPM (rev/min)/5252 (hp-min/ft-lbs-rev)

Lets say that your Continetal A-65 engine makes 150 (ft-lbs) of torque at 2300 rpm, what would its horsepower be?

Horsepower = 150 (ft-lbs)*2300 (rev/min)/5252 (hp-min/ft-lbs-rev)
Horsepower = 65.7 hp

Shown below is set of curves for a Continental A-65 engine. These curves show how things like engine horsepower, manifold pressure, fuel consumption, and prop load change with rpm. You can see that full throttle horsepower changes directly with rpm. That is to say that there is straight-line relationship between horsepower and rpm over the rpm range given in the chart. It turns out, that there is also a straight-line relationship between manifold pressure and horsepower over the same rpm range. This is true because engine torque is proportional to the manifold pressure over a specific range of engine rpm. We can use this fact to estimate the amount of horsepower our engine is making if we know the rpm and the manifold pressure.



Continental A-65 engine performance curves.

In summary, if we know the engine's rated horsepower, rpm, and manifold pressure we can figure out the approximate horsepower for any manifold pressure and rpm combination. Here is how it works:
Say our A-65 is rated for 65 horsepower at 2300 rpm at 29" of manifold pressure. If we fly our Champ around and happen to notice that our rpm is 2000 and our manifold pressure is 23" what will the horsepower output of the engine be?

Formula #1:

Horsepower = Actual RPM/Rated RPM * Actual MP/Rated MP*Rated HP

Horsepower = 2000/2300*23/29*65
Horsepower = 44.8

So if we could get the Champ hooked up to 45 horses and got them all going in the same direction at a full gallop with a good head wind we should be able to get the plane into the air. Even at $4.00 a gallon, feeding the A-65 has got to be cheaper than feeding 45 horses.

This is not quite the whole story though. To really get an accurate comparison of horsepower we have to also include the effect of temperature. Since engines are normally rated at a standard air temperature of 59 F, we need to take into account any variation from that temperature. In order to do this, we need to do it on an absolute temperature basis so we need to add 460 F to both the standard air temperature and the actual air temperature the engine is operating at. So, for our example if the actual air temperature on the day of the test is 70 F then the actual horsepower produced by the A-65 would be:

Horsepower = Actual RPM/Rated RPM * Actual MP/Rated MP*Standard Temperature/Actual Temperature*Rated HP
Horsepower = 2000/2300*23/29*519/530*65
Horsepower = 43.9

Good, we now only need 44 galloping horses.

You can see that a nonstandard air temperature does not have a large effect on engine horsepower unless it differs significantly from standard temperature.

Calculating Aircraft Performance

We are now ready to calculate how changes in horsepower can affect aircraft performance. The relationship is actually pretty straight forward. It is as follows:

Thrust horsepower = Horsepower/Eff_{prop}

Drag * Velocity = Thrust horsepower
Horsepower = Eff_{prop} *Drag * Velocity

The horsepower divided by the propeller efficiency is often referred to as Thrust Horsepower and varies indirectly with the aircraft speed. This means that as the aircraft travels faster, there is less thrust available to overcome drag. We know that drag equals one half times the density of the air multiplied by the velocity squared, then times the coefficient of drag, and finally multiplied by the area of the object. In equation form it looks like this:

Drag = 1/2*Rho*V^2*Cd*Sref

Since we want to compare how a change in horsepower changes the speed of the aircraft and we don't plan to change the area of the object, or the coefficient of drag or the density of the air, and the propeller efficiency will not change a great deal for small changes in speed, we can simplify this formula considerably. It can now become horsepower is proportional to velocity cubed, or in formula form:

Horsepower = constant * Velocity^3

Based on this relationship, we can say that a change in velocity of an aircraft will be proportional to the cube root of the change in horsepower or in formula form:

New Velocity/ Old velocity = (new horsepower/old horsepower)^1/3

or better yet,

Formula #2:
New airspeed = Old airspeed *(new horsepower/old horsepower)^1/3

We are now ready to predict how a change in horsepower will change the speed of our aircraft. It involves three simple steps.

Step 1 –Fly the airplane (the most fun). While flying your aircraft at your normal cruise settings for the engine, write down the rpm, manifold pressure and cruise airspeed.

Step 2 – Calculate the horsepower the engine making at the power setting you wrote down based on Formula #1.

Step 3 – Select a new horsepower and calculate your new airspeed based on formula 2.

Now all we need is an airplane to try this out with. How about Roger Smith's Tri Pacer. Roger always wants to go higher and faster.

Roger’s tried and true Tri Pacer.

Roger and I went flying in his Tri Pacer on a beautiful day and soon found ourselves doing Lazy Eights and Chandels. Oops, back to work. We measured the following performance for his Tri Pacer which has a 150 hp Lycoming O-320 engine:

Density altitude = 9600 ft
Weight = 1750 lbs
Indicated airspeed = 104 mph
True airspeed: 119 mph
Manifold pressure: 21.5”
Engine RPM: 2570

From Formula #1:

Horsepower = 21.5/29.92*2570/2700*150
Horsepower = 102.6

You say, wait a second, that is only about two thirds of the engine’s rated horsepower. Well you would be right, that’s what happens to rated horsepower at a density altitude of 9600 feet and a propeller that isn’t turning at the engine’s rated speed. Roger wants to go faster though by installing high compression pistons in his engine so it can develop a 160 hp at a manifold pressure of 29.92” and 2700 rpm. What would his new true airspeed be at this higher horsepower?

From Formula #1:

New horsepower = 21.5/29.92*2570/2700*160
New horsepower = 109.4

From Formula # 2:

New true airspeed = Old airspeed *(new horsepower/old horsepower)^1/3
New true airspeed = 119* (109.4/102.6)^1/3
New true airspeed = 121.6 mph

Roger would get almost a 3 mph increase in cruise speed with the high compression pistons in his Tri Pacer. But what would happen if Roger just had his propeller re-pitched to produce 2700 rpm at the cruise conditions?

From Formula #1:

New horsepower = 21.5/29.92*2700/2700*150
New horsepower = 107.8

From Formula # 2:

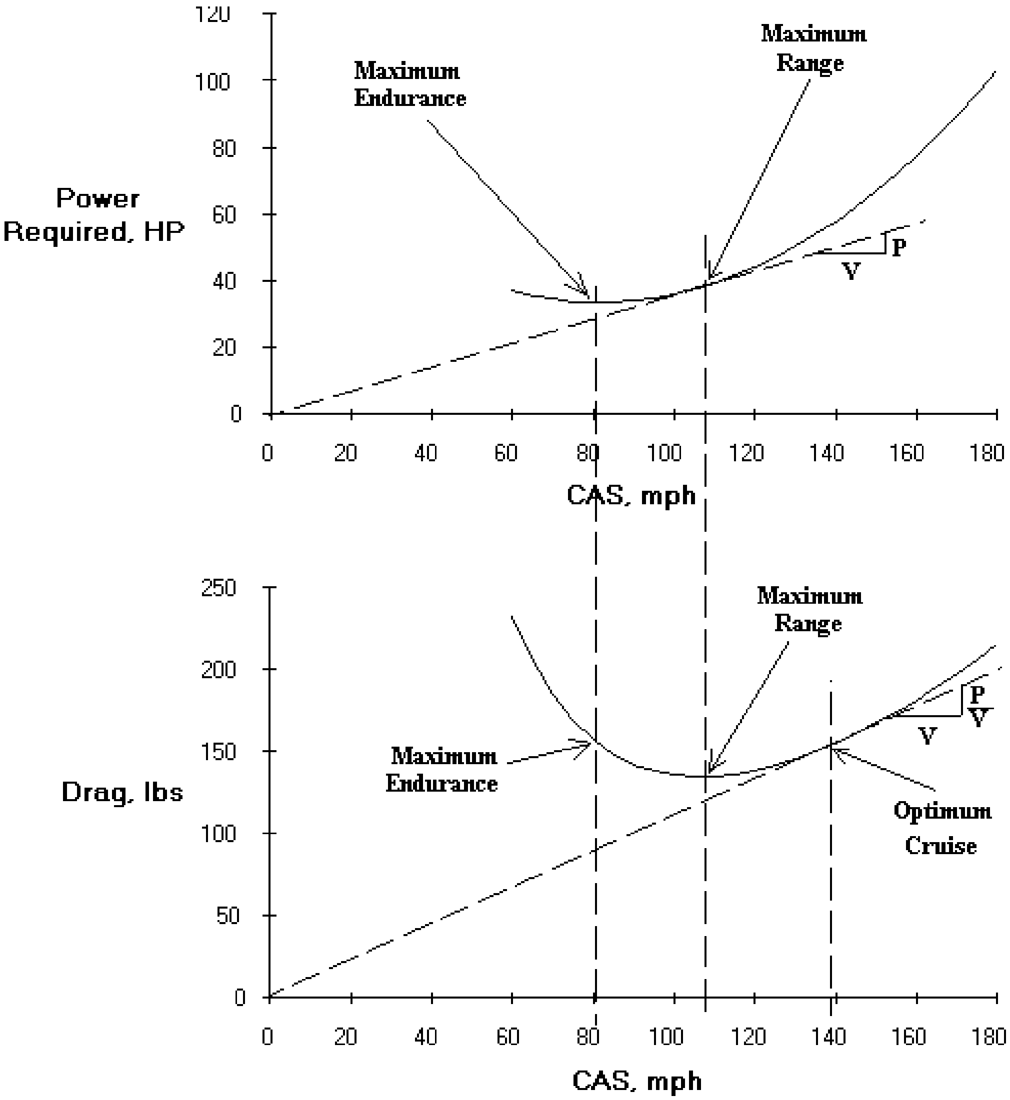
New true airspeed = Old airspeed *(new horsepower/old horsepower)^1/3
New true airspeed = 119* (107.8/102.6)^1/3
New true airspeed = 121.0 mph

Roger would get almost the same increase in airspeed at a fraction of the cost. The only downside to this method of increasing horsepower, would be that in a descent at full power Roger would need to reduce his throttle to prevent over speeding of the propeller.

If you know Roger, you know that he is never satisfied. Not only does he want the Tri Pacer to go faster, he also wants it to climb better. Lets see what this additional horsepower would do for the climb rate of the Tri Pacer. The climb rate of the aircraft is determined by what is referred to as, Excess Horsepower. It takes a minimum amount of horsepower to keep an aircraft in the air at its Best Rate of Climb airspeed. Excess Horsepower is the horsepower left over, that can be used to climb. Most light piston aircraft use about 50% of their horsepower to stay in the air at their best rate of climb airspeed, but rather than estimate it, lets go flying and measure it. All we need to do is to fly at our Best Rate of Climb airspeed, Vy, and throttle back until we are neither climbing or descending. We can then use Formula # 1 to calculate the minimum horsepower required for this airspeed. The following website provides some additional explanation of power requirements vs airspeed including the Carson Speed, which we all know about, right?

http://www.eaa1000.av.org/technicl/perfspds/perfspds.htm#Maximum_Endurance

Shown below are two graphs for a typical light aircraft, from the article noted above. One graph shows power requirement vs airspeed and the other shows drag vs airspeed. If we look at the graph of power vs airspeed and the airspeed for maximum range, we find that this is also the minimum drag airspeed shown in the second graph. This airspeed is also equal to the best glide speed and is also equal to your best rate of climb airspeed (Vy). So, if you know your best glide airspeed you know a lot of things about your aircraft. Your best angle of climb airspeed (Vx) is equal to Vy divided by1.3, and so is your maximum endurance airspeed, Vbe. Vc, your Carson Speed is equal to Vy times1.3.



Graph Showing Power and Drag vs Airspeed for a Typical Light Aircraft.

OK, back to figuring out Roger's Tri Pacer climb rate. We recorded the following engine parameters while flying at the best rate of climb (Vy) airspeed in level flight:

Density altitude = 9600 ft
Gross Weight = 1750 lbs
Best rate of climb airspeed = 84 mph
Manifold pressure: 19.2"
Engine RPM: 2300

From Formula #1

Minimum horsepower = 19.2/29.92*2300/2700*150
Minimum horsepower = 82.0

So it takes about 82 horsepower to keep Roger's Tri Pacer in the air at his best Rate of Climb airspeed, at a gross weight of 1750 pounds at a density altitude of 9600 feet. Now lets find the excess horsepower available for climbing. We now go to full power in the Tri Pacer, and as the g suits inflate and the blue sky begins to darken as we approach the limits of the Earth's atmosphere, we try to maintain our best Rate of Climb airspeed and log the RPM, manifold pressure, and rate of climb. This time we get:

Density altitude = 9600 ft
Gross Weight = 1750 lbs
Best rate of climb airspeed = 84 mph
Manifold pressure: 21.6"
Engine RPM: 2490
Indicated ROC = 390 fpm

Again from Formula #1:

Available Horsepower = 21.6/29.92*2490/2700*150
Available Horsepower = 99.9 hp

Notice that this is a little less horsepower then the engine developed at full power in the cruise test. The reason is, that with a fixed pitch propeller and at the lower airspeed used in the climb, the engine can't turn as high an rpm as it did in cruise. OK, time for another formula.

Formula #3:
Excess Horsepower = Available Horsepower- Minimum Horsepower

So, in this case for the Tri Pacer:

Excess Horsepower = 99.9-82.0

Excess Horsepower = 17.9

If we know one other thing, and that is propeller efficiency at the climb airspeed, we can calculate the rate of climb. It is reasonable to assume a propeller efficiency of 80% at normal climb speeds for a fixed pitch propeller. The formula for climb rate is:

Formula #4

Rate of Climb = Excess Horsepower*33,000*Eff_{prop}/Weight

Rate of Climb = 17.9*33,000*0.80/1750
Rate of Climb = 270.0 fpm

But wait a minute, the vertical speed indicator (VSI) said that we were climbing at 390 fpm, how come we only calculate 270 fpm. Well, it could be because the VSI is out of calibration, or the engine rpm was jumping around so much that we didn't read it right, or that I don't know what I'm talking about. Personally, I think all Tri Pacers are issued a "special" VSI that improves the aircraft performance (just kidding Roger), but since we are really interested in relative changes lets stick with the 270 fpm for now.

We can now see what a 160 horsepower engine would do for Roger's climb rate. Remember that we are only getting 160 horsepower when we are at 29.92" of manifold pressure and 2700 rpm. So we need to see what the actual available horsepower is at climb conditions. So from Formula #1

Available Horsepower = 21.6/29.92*2490/2700*160
Available Horsepower = 106.5 hp

Using Formula #3 and #4:

Excess Horsepower = Available Horsepower- Minimum Horsepower

So, in the case of the Tri Pacer:

Excess Horsepower = 106.5-82.0
Excess Horsepower = 24.5

Rate of Climb = Excess Horsepower*33,000*Eff_{prop}/Weight
Rate of Climb = 24.5*33,000*0.8/1750
Rate of Climb = 370 fpm

This is a substantial increase from the previous climb rate of 270 fpm. So, while the increase in horsepower from 150 hp to 160 hp does not do a lot for cruise speed it really makes a big difference in climb rate. The reason is that, speed increases in proportion to the cube root of the increase in horsepower, while climb rate increases based on the excess horsepower available. Since excess horsepower is usually about 50 % of your total horsepower, adding a little more horsepower, makes a big difference.

Note that the propeller efficiency can have a big effect on climb rate. Another way to do this calculation that does not rely on estimating the propeller efficiency, is to use the measured climb rate at full power instead of calculating the climb rate. If you do this though, be sure to time the climb to determine the climb rate. VSIs are subject to errors such as a leaking static system, and static offset. You should also check your tachometer for accuracy. You can use an optical tachometer to calibrate it. These efforts to get accurate data will generally give you a more accurate answer.

In the next Tech Note, I will show you how reducing the drag on your aircraft can make a big difference in your cruise speed and is usually a much better way to increase speed than to add more horsepower.