Optimizing Plane Performance by Finding the "Right" Prop
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This is not an article for the meek or timid. Finding the right prop for your engine and airframe the engine is mounted on can be a daunting process if done right. There are many reasons for this.

1. Every engine has its own unique torque and horsepower characteristics. The same prop will operate differently on different engines.
2. Prop designs are different depending on manufacturer and engine type. For a given diameter and pitch you will find wide props, narrow props, thin props, thick props, and even almost pointed props. What's more, the designated pitch of a prop is more or less the manufacturer's guess. An 8" pitch prop from 1 manufacturer may be different from another's. Props for four cycle and gas engines are generally wider and thicker to better match the higher torque outputs and lower speeds of these engines.
3. If that weren't enough to confuse the average RC flyer, consider the fact that the effective pitch of a prop changes in flight with changes in engine RPM and forward speed of the plane! In general, the higher the RPM of the engine or the faster the speed of the plane the smaller the effective pitch of the prop. In many ways the prop acts like an automatic transmission. It provides a "low gear" (high pitch) for acceleration and a "high gear" (low pitch) for efficient cruising.
4. A prop of a given diameter and pitch will work differently depending on the drag characteristics of the airframe the prop is attached to and the flying style of the pilot. A prop designed for speed will not work well on a high drag airframe like a bipe that will not go fast no matter how hard you try. Nor will it work well if you do a lot of vertical maneuvers and expect constant speeds through those maneuvers.
5. The performance of a prop can be significantly affected by changes in meteorological conditions. A prop that works well at sea level may not work so well at an elevation of 2,000 feet where the pressure is lower. Similarly, a prop that works well in cool weather at 50°F may not work so well with summertime temperatures in the 90's.

Before going any further, it needs to be said that any plane will fly with any reasonable choice of props. If boring holes in the sky is your only objective, then read no further. If you are interested in optimizing the performance of your plane, then read on.

The process of optimizing performance through proper prop selection involves making educated guesses on prop type, verifying those guesses through flight testing, and settling on the prop that feels right to you. There are a number of options available to you for doing this ranging from easy and cheap to time consuming and expensive (Have you priced a composite 24 x 6 prop lately?). Before discussing these options, some words on engines and engine design are in order.

Basic Engine Design Parameters:

There are two basic parameters engine designers use to design engines. The first of these is called torque. For single cylinder engines, you can think of torque as the amount of useful rotational energy the engine produces at the crankshaft in one complete cycle of the engine. Torque is a measured quantity obtained from an operating engine. The other parameter is the energy available at the crankshaft over time. It is called shaft horsepower or simply horsepower. Horsepower is a calculated parameter. It is obtained by multiplying measured torque at a given RPM by the RPM at which the torque was measured.

Torque and horsepower vary with engine RPM. Torque and horsepower curves are available from engine manufacturers or can be sometimes be found in RC publications. Relationships between torque and horsepower vary widely with engine design. For 2-cycle engines, peak torque usually occurs at a lower RPM than peak horsepower. Four-cycle alcohol and gas engines produce greater torque than 2 cycle engines and produce that torque at lower RPM's.

Once an engine is manufactured, the ability to change torque and horsepower characteristics is limited to changing carburetor size or removing exhaust restrictions. That means for most RC flyers the key to getting optimum performance in RC applications is to match the external engine load (i.e. the propeller) with the fixed capabilities of the engine (i.e. torque). In general, you will have an optimum prop/engine combination when the engine at full throttle operates at an RPM at or close to the RPM where peak torque is produced. Since there are a number of diameter and pitch combinations that can meet this requirement, the task ahead is to find that unique combination of diameter and pitch which matches performance expectations (speed, vertical ability, acceleration, etc) and flying style.

Provided below are a number of options for finding the right prop that will result in optimum performance and meet your performance objectives. The options are listed by degree of difficulty and commitment to succeed.

Option 1: Ask Somebody What Prop to Use

Every club has members with varied interests who from experience have found props that work well for various engine/airframe combinations. Ask them, and take their advice as a starting point. Their advice will probably work for you; however, there's always room for improvement. Your chance of success in using this option will be much better if the advice comes from someone who flies the same way you do or want to do.

Option 2: "Rule of Thumb" Performance Enhancements

If you want to do the work yourself, this is the easiest way to change or improve engine/prop performance. It works best when you are starting with a prop that is already a good fit or close to a good fit for your engine; i.e. the engine runs at an RPM that is at or close to the peak torque RPM of the engine.

1. If you want to increase the speed of your plane, reduce the diameter by 1" and increase the pitch by 1".
2. If you want to reduce the speed of your plane and increase its vertical performance, increase diameter by 1" and reduce pitch by 1".
3. Sometimes the cure for a sluggish bipe is to increase the diameter by 1" and reduce the pitch by 1".
4. The general rule for changing from a two-bladed prop to an equivalent three-bladed prop: decrease diameter by 1" and increase pitch by 1".
5. The general rule for changing from a three-bladed prop to an equivalent two-bladed prop: increase diameter by 1" and decrease pitch by 1". Some RTR trainers come with somewhat bland three-bladed props. To improve the performance of these trainers at minimal cost, replace the three-bladed prop with a two-bladed one having a 1" greater diameter. Keep the pitch the same.

6. You fly year-round and have a great prop/engine combination that works well at 50°F. How do you get the same performance in the middle of summer where the temperature may be 90° or higher? In general a 40° increase in temperature will result in a 7% reduction in prop thrust. Try increasing diameter and/or pitch by 1" for flying in the hotter weather. (See Option 5 for a more exact way to optimize props for changing meteorological conditions.)
7. You live and fly at sea level, but at times fly at a field with an elevation of 2,000 feet. You have a great prop/engine combo for flying at sea level. How do you get the same performance at the field with the higher elevation? Atmospheric pressure is about 2" Hg lower at the higher elevation. This lower pressure results in about a 7% reduction in prop thrust. Try increasing diameter and/or pitch by 1" for flying at the higher elevation. (See Option 5 for a more exact way to optimize props for changing meteorological conditions.)

<u>Option 3</u>: Use the Manufacturer's Prop Recommendations

Engine manufacturers provide a range of prop sizes in their instruction manuals, which through testing have been determined to provide optimum performance in their engines. The recommended props usually cover a variety of diameters and pitches. The trick is to choose the one that meets your performance expectations and flying style, while matching the performance requirements of the aircraft type being flown. You don't have to stay with the recommended lists of props. The list can be judiciously expanded to include props of different diameters and pitches using the Rules of Thumb provided in Option 2. Use the following guidelines for picking the right prop from these lists.

1. If speed is your goal, try the smaller diameter higher pitch props in the given range. One option to try is to take the highest pitch prop in the range, decrease its diameter by 1" and increase the pitch by 1". If this does not satisfy your need for speed, consider installing a bigger engine.
2. If you are flying a bipe, the large diameter smaller pitch props tend to work the best.
3. Scale airplanes, whether they are Cubs or P-51's should be flown at scale speeds. This means that in general, appropriate props are those which do not have the largest pitches. Slow planes like the Cub should be flown with large diameter low pitch props. Planes

like the P-51 need props with intermediate diameters and pitches. Experimentation will provide the one that looks and feels right in the air.

4. Pattern and aerobatic aircraft are the most difficult ones to prop adequately since they require unique combinations of speed and vertical performance. In addition, the pilots who fly in this category are arguably the most skilled and demanding of anyone in the hobby. The best way to find a prop for this style of flying is to ignore the lists and find someone who flies a similar plane and engine and go with their recommendations. You can always use the Rules of Thumb discussed in Option 2 to fine-tune their suggestions to satisfy your personal preferences and flying style.
5. Some tricycle gear planes may not have enough ground clearance to accommodate a recommended prop for the engine you are using. Try reducing the diameter by 1" and increasing the pitch by 1". It might work for you.

<u>Option 4</u>: Use the Torque Curves for your Engine

Having a copy of the torque curve for the engine you're using will easily let you find the range of props appropriate for your engine. The general approach using this option is to mount a variety of props on your engine, take full throttle RPM measurements, and compare the measured RPM values against the peak torque RPM (or range of RPMs) for the engine. The problem using this option is that torque curves are not readily available for a large number of engines used in the hobby. You have to work to find them.

In some engines, torque falls off rapidly with RPM past the peak torque RPM. In others, torque is relatively flat over a large RPM range. Engines with flat torque curves generally will produce higher torques at higher RPMs and will therefore support a wider range of prop diameters and pitches. You will have an easier time matching props to your performance expectations and flying style with engines that have flat torque curves.

Use the following steps for finding the right prop using torque curves.

1. Identify a collection of props of various diameters and pitches you believe will be appropriate for your engine. Include props from different manufacturers, as props with the same diameter and pitch can be significantly different from a performance perspective depending on who made them. Try some you don't think will work. You might be surprised.

2. Mount each prop on your engine and measure full throttle RPM.
3. Decide on an RPM range you want to evaluate relative to peak torque RPM (i.e. +/- 200, 400, etc). This range should be larger for torque curves that are relatively flat.
4. Cull out those props that fall outside the your chosen range. If you chose the right collection of props in 1. above, you should end up with a number of props having different diameters and pitches which should be optimum or close to optimum for your engine.
5. Use the previously discussed Rules of Thumb to choose those you think will meet your performance expectations and flying style.
6. Make your final choice by flight testing.

Option 5: Perform Static Thrust Testing

This is the only option that actually measures the real performance of a prop: the movement of air rearward that results in a forward thrust force. Larger diameter lower pitch props tend to move a lot of air slower while smaller diameter higher pitch props tend to move a smaller amount of air faster. There are many combinations of diameter and pitch that will result in the same thrust force. The key to using this option is to find the maximum thrust produced by the engine and then find the diameter and pitch combination producing this thrust that matches your performance expectations and flying style.

The real benefit of using this option is to be able to predict prop performance under different values of engine RPM and meteorological conditions. It essentially removes the guesswork associated with the Rules of Thumb discussed previously. The problem of using this option is that it involves a lot of work (including some serious number crunching), and should only be considered if you are a serious competitor looking for a performance edge.

The general approach for using this option is as follows.

1. Start with a prop having a diameter and pitch you know works well for you under a given set of flying conditions. Using this prop as a baseline, choose a range of props with slightly different diameters and pitches. Throw in a couple of different manufacturers.
2. For each of the props identified in 1. above measure static thrust and RPM at full throttle conditions. These measurements need to be as accurate as possible. Make careful note of atmospheric

temperature and pressure. You will be using these values in future calculations.

Measuring static thrust is the easiest part of this option and is the most fun. You will need two 3 to 4 foot lengths of heavy chord tied into loops and a digital fish scale having a capacity that approximately matches the weight of your plane. Place a loop of chord around each side of the horizontal stab and attach the ends of the 2 loops to the fish scale. Run the engine at full throttle and gently but steadily pull back on the fish scale until you can hold the plane in place against the thrust of the prop. Read the value of thrust on the fish scale. With a little practice you can get consistent thrust readings within 1 to 2 ounces in calm wind conditions. These thrust measurements will be used in future calculations.

3. Convert the temperature measured in 2. above from Fahrenheit to Kelvin in two steps as follows:

   Convert temperature from Fahrenheit to Centigrade

   $$°C = (°F – 32)5/9$$

   Convert Centigrade temperature to Kelvin

   $$°K = °C + 273.16$$

4. Calculate the density of air in grams per liter using the values of atmospheric temperature and pressure noted in 2. above as follows:

   $$d = (11.79)P/T$$

   where P = atmospheric pressure in inches of Hg
   T = atmospheric temperature in °K

5. Convert the diameters of you props from inches to meters using the following:

   $$D(\text{meters}) = D(\text{inches})/39.37$$

6. Using the thrust and RPM values for each of the props measured in 2. above, calculate the Thrust Coefficient , C_t, for each prop using the following equation:

$$C_t = 1000F/dn^2D^4$$

where F = measured thrust in ounces
d = Air density in grams per liter
n = Propeller RPM
D = Propeller diameter in meters

The calculated Thrust Coefficient is unique to the physical characteristics of each prop. As a result, once you know C_t for a given prop you can use it to calculate expected thrust for any set of atmospheric conditions and engine RPM. C_t is also independent of engine type. Once calculated for a prop you can predict the thrust performance of that prop <u>on any type of engine</u> by measuring RPM and knowing atmospheric conditions. (See 7. below)

7. Knowing the Thrust Coefficient of a prop you can calculate the thrust produced by that prop for any set of atmospheric conditions and engine RPM. Rearranging the terms in the equation for C_t, you end up with the following:

$$F = C_t dn^2D^4/1000$$

Here's a good example of where you might want to use this option. You have a great prop that flies well at sea level at a temperature of 90°F, but your next meet is in Denver where the atmospheric pressure is about 24"Hg and the temperature is expected to be 50°F. How do you find a prop for Denver that works as well for you as your sea level prop? If you've gone through all the steps of this option, you should have a complete catalogue of Thrust Coefficients for all the props in your inventory. Once you get to Denver, run each of the props and measure their full throttle RPM. Knowing Denver atmospheric temperature and pressure, calculate static thrust for each of the props using the thrust equation in 7. above. Pick the prop that gives you the same thrust as the one that works well for you at sea level.

Some closing thoughts on use of static thrust information you might find useful for optimizing the performance of your plane. If you don't want to go through the extensive analysis required by this option at least be aware of the following "Rules of Thumb". They fall directly out of the equations presented above.

Affect of Engine RPM on Static Thrust:
For a given prop, increasing engine RPM by 5% (8,000 to 8400, 10,000 to 10,500, etc) will increase static thrust by 10%. So for increased performance at no cost, tweak that carburetor.

Affect of Atmospheric Temperature on Static Thrust:
For a given prop, the lower the air temperature the greater the static thrust produced. The thrust produced at a temperature of 50°F will be 9% greater than the thrust produced at a temperature of 95°F. If flying in hot conditions, you might want to increase diameter and/or pitch to regain some of your lost performance.

Affect of Atmospheric Pressure on Static Thrust:
For a given prop, the greater the air pressure the greater the static thrust produced.

Pressures at sea level normally range from 30" Hg to 29"Hg. Large storms may lower this to 28"Hg. The thrust produced by a prop at a pressure of 30"Hg will be about 7% greater than the thrust at 28"Hg.

Field elevation may have a greater impact on thrust than normal pressure changes. The atmospheric pressure at Denver (El 5,000 ft) is about 24"Hg. A given prop run at sea level will produce about 20% more thrust than the same prop run at Denver conditions (assuming temperature and engine RPM are the same for both locations). If you normally fly at sea level and you find yourself at a field with a higher elevation you might try increasing the diameter and/or pitch of your prop to regain some of your lost performance.

Affect of Prop Diameter on Static Thrust:
In general, the greater the diameter of a prop the greater the static thrust produced. But you have to be careful with this one. The magnitude of the thrust increase may not be a big as predicted by the equations. Assume you have two props with the same thrust coefficient being run at the same RPM. One has a 10% greater diameter than the other. The one with the greater diameter will produce 46% greater static thrust. In reality the larger prop will probably need a bigger engine to achieve the same RPM and get the larger thrust capability out of the prop.

Conclusions:

There are a number of factors that can affect the performance of props. Options are available to the average flyer to improve the performance of their planes by experimenting with prop sizes and types. Some take more work to accomplish than others but the good news is you get to verify the impact of your changes by flying!

Happy Prop'ng!

Steve Grabowski