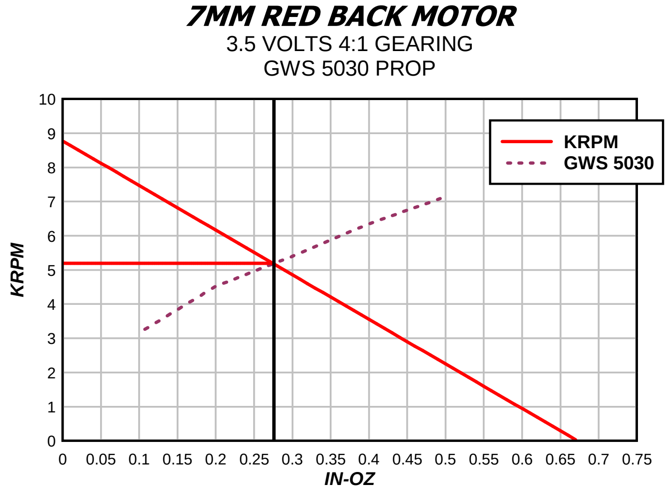
Electric Motor Systems
A Rubber Analogy
Stew Meyers

A rubber power system stores energy mechanically in the wound motor which drives the prop directly as it unwinds. An electric power system stores energy chemically in a battery which releases it as electric current to the motor which converts it to mechanical power to drive the prop. There is an electric circuit loop that allows current to flow from the battery through wires to the motor and back to the battery to complete the path. It's the current flowing through the motor that supplies the mechanical power to the prop. We'll discus the battery later, now let's look at how a motor works.

When current passes through a wire it sets up an magnetic field around it. In motors the wires are wound into coils to intensify the magnetic field produced. This magnetic field reacts with the permeant magnet field of the motor to produce a force that drives the motor. The motion would stop when the magnetic fields algin with each other, but there is a commutator which switches the current to the next coil to produce a continuous rotation. The force, or in the case of a rotary motor, the torque is a function of the number of turns in the coil and the current passing through it. DC motors have a linear torque constant that is the ratio of torque to current.

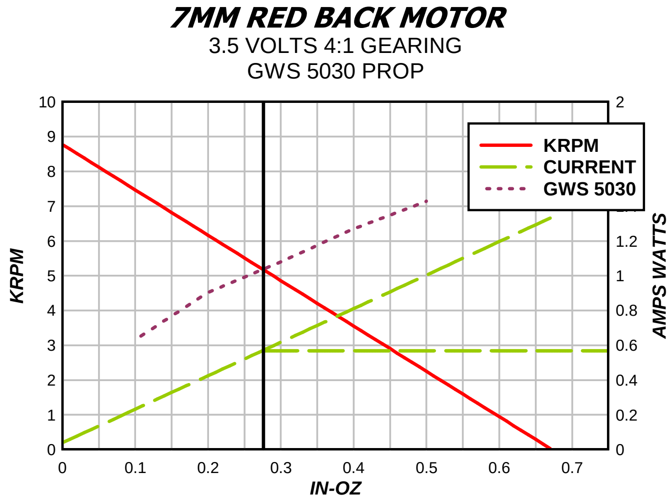
Rubber motors are essentially a torque device, you wind them up and they store energy as torque. This torque is independent of the rpm. A prop can also be thought of as a torque device. The speed at which the prop spins is a function of the size of the prop i.e. diameter and pitch and the torque applied. It so happens, the speed (rpm) of the prop is proportional to the square root of the applied torque.

As in the case of a rubber motor, the electric motor drives the prop by applying torque. However the torque of an electric motor is not constant, but is a function of its rpm. For a given voltage, the speed of an electric motor (rpm) is a function of a linear voltage constant and the load applied to it by the prop. The prop then loads the motor by drawing a current that is a linear function of the torque associated with that rpm. The constants result in straight lines for the rpm and current curves when they are plotted against torque. This is easiest to see in a graph.

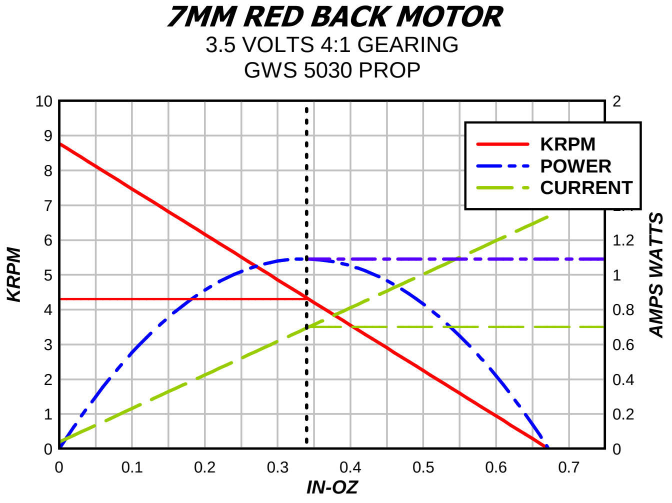


In the first graph, a vertical torque reference line has been drawn in where the propellor load curve intercepts the rpm curve. Torque is read off the horizontal axis. This defines the operating point of the motor in terms of torque and rpm. The motor speed in krpm is read off the left axis. A horizontal reference line has been drawn in to aid in this.

Since current is a linear function of torque, the intersection of the torque reference line and the current curve defines the current drawn by the prop at the operating point. This is read off the right vertical axis. A dashed horizontal reference line has been drawn to aid in this in the graph below.



Power is the product of speed and torque. If we multiply the motor speed in krpm by the torque in in-oz and a constant of 0.74, we get power in watts. Since rpm is a linear function of torque, the resulting power curve is a parabola rising from zero at zero torque to end at zero rpm. The maximum power of a DC motor is produced at the operating point that is defined by operation at half the no-load speed and half the stall torque. This is indicated in the graph below by the dotted vertical reference line. Read the torque off the horizontal axis where this reference hits it. Using the dash-dot horizontal reference line at this operating point, one can read max power off the right axis. This graph is a little busy, but lets drop down the vertical reference line to where it crosses the rpm curve. A solid



horizontal reference line is drawn here, following it to the left axis we can read off the rpm at max power. Similarly dropping further down the vertical reference line to where it crosses the current line and drawing in another horizontal reference line (in this case dashed) we can read the current at max power off the right axis.

(These graphs include the effect of a 4:1 gear box. The rpms are 1/4 of the motor rpm and the torque is four times the motor output torque.)

As we put more of a load on the motor by larger props, the vertical operating point reference line moves to the right as the torque is increased and the rpm is reduced. Naturally the current increases with torque. Once the peak power point is exceeded, the motor continues to draw more current, but actually produces less power out. The extra power is dissipated as heat and can in the extreme case can result in destruction of the motor. Heat dissipated = current through the motor squared, multiplied by the terminal resistance of the motor.

Electric motors like to run at high rpms and low current to reduce heating. If you hang too big a prop on an electric motor you can move past peak power and bad things happen. Too small a prop results is not producing much power. Small high rpm props don’t match up well with light, slow or draggy airframes. Fortunately you can use gears to let the motor run at high speed and turn a larger prop at lower speed which is a better match to the airframe.

With rubber motors the torque is a function of the width of the rubber and the percent of permissible turns. With an electric motor, the current and therefore torque available from the motor is a function of battery amp-hour capacity as well as the percent of charge and the motor constants, somewhat analogous to both rubber width and length. The percent of charge of a battery is analogous to the percent of permissible turns. As power is drawn from the battery, the voltage runs down and the current produced is reduced, some what analogous to the reduction of torque as the rubber motor unwinds. The shorter the rubber motor, the more quickly it will run down. The smaller the amp-hour rating of the battery, the quicker it will run down. The width analogy comes into play, when you hook up a motor to a too small an amp-hour rated battery. It’s like using a rubber motor that is too small in cross section, the prop will not turn very fast and barely produce any power. Too small a battery will have a large initial voltage drop and produce less power in the motor, the battery also will not tolerate this very well and can overheat and be damaged. The message here is you must use a battery that is has a enough capacity for the job.

The electric motor system includes the battery, prop, and gearing all of which affect performance. This is a little more complicated than rubber motor performance which is dependent on rubber cross section, length, percentage of winds and prop. I hope this article helps explain why.

Selecting an Electric Motor System

Stew Meyers

Well so much for theory and analogies, in practice, how do you select a power system for a free flight model? First of all let’s rule out brushless systems as too expensive unless you really need the lightest possible motor. For brushed motors, you initially want about 2 watts of input power per ounce of all up weight for good climb. (Note the power in the preceding graphs was out put power.) For a scale model, I like to use a scale diameter prop. You want to find a motor and gearing that will drive your prop while operating in a efficient range and produce the required power. This will define the voltage and current needed. You then select the battery that will supply this input power.

The biggest advance in electric power has been battery chemistry. Lithium Polymer cells have three times the capacity of Nicads. They do have to be treated with respect however. Let’s look at low vs. high voltage systems. The fewer number of cells, the simpler the system, but the lower the voltage. For the same power, a low voltage system requires higher current. Higher current results in more voltage drop and losses in switches, connectors, and wiring. With Nicads the nominal voltage is 1.2 volts per cell, this drops to about 1.1 under load. NiMh cells run about a tenth of a volt less. Lipolys have a nominal loaded voltage of 3.7 volts per cell. They also can not be discharged below 2.8 volts per cell with out permanent damage. The use of a Lipoly dictates a timer to limit depth of discharge. For reasonable free flight models one or two cell Lipoly batteries are the way to go. A fuse is very good idea and not hard to implement. There must be some provision to remove the battery from the circuit after flying to prevent it being drained by the timer over time. Good practice would be to provide a way to remove the battery from the airframe for charging. I quite often don’t bother.

For practical free flight with Lipolys, the battery is chosen to provide enough power for 10 minutes of flight. Multiply the amp-hr rating of a battery by 60 you have amp-minutes. Drain the battery in 10 minutes and you operate at a 6 “C” rate. You can’t always trust the rating on batteries, but in general you don’t want to operate Lipolys at more than 8 times their mAhr rating. Some will not even tolerate this very well. Nicads will stand the abuse of drawing much higher current ratios, but still end up being heavier.

You don’t have to plot the motor constants to figure out how to use motors. You just need to know the motor peak power and current at the operating voltage. It also helps if you know the rpm at peak power. You also need to know the prop and gear ratio that will load it to that point or a point just a little shy of this. It’s important to know the current that the motor is drawing from the battery as well as the voltage. Both the motor and battery performance are highly dependent on current.

It is easy to measure voltage, but not so easy to measure the current since an ammeter must be placed in the current loop. This usually is done by inserting the shunt or ammeter between the battery and the rest of the circuit, so you can see if your motor is trying to draw too much current or if the battery voltage is sagging too much under load. There are several power meters that combine the ammeter and voltmeter function and as a bonus show power.

If you don't measure the current at least measure rpm with a tach when you change props to make sure you are above the max power rpm. This will assure you not loading down the motor too much. If you know the voltage constant of the motor, the Kv, you can multiply this by the operating voltage to get no load rpm. Divide this by 2 and again by your gear ratio to get the max power rpm.

Let's look at a specific example, converting a rubber power design to electric free flight. My 18" Bristol Scout has 117 sqin wing area and weighed 47 grams without rubber, but about 15 grams was ballast and prop. I flew this model on 8-10 grams of rubber. Say, 55 grams all up weight (55/117= 0.47 grams/sqin or about 2.4 oz/sqft and 55 grams is about 1.9 oz). For brushed motors, you initially want about 1.5 to 2 watts of input power per ounce of all up weight for good climb. In this case that's 2.9 to 3.8 watts. The scale prop diameter is 5 inches.

Gordon Johnson has published data for the 7mm pager. This comes in several winds and Gary Jones developed a 7mm 4:1 gearbox for it. With the red back 2.3 ohm motor it's a great combination with a GWS 5030 prop and a single LiPoly cell. At 3.5 nominal volts from a LiPoly cell the red back motor draws 630 ma for 2.2 watts in and turns the 5030 at 5.1KRPM while the motor runs at 20.8 KRPM. The peak power point is 690 ma and 17.6 KRPM. The motor prop and gearbox weigh 5.6 grams. Ordinarily, the battery is assumed to weigh as much as the motor; however the Atomic Workshop series of LiPoly batteries has a very high specific energy. A 130 mahr Atomic Workshop weighs only 3.7 grams with a connector and more than does the job. My tests show it staying above 3.8 volts for several minutes while powering a red back motor driving a 5030 prop at 2.8 watts input.

So where are we? 5.6 grams motor and prop, 3.7 grams battery, 1.5 grams timer. 1.2 grams fuse and holder for 12 grams all up. Remember the 15 grams ballast and prop, and 8 grams rubber? With a WWI bipe we're ahead of the game. The empty weight was 47 grams or 1.6 oz; that's about what the electric conversion weighs with structure to hold the electric components. Wing loading is now 2.0 oz/sqft; the input power of 2.8 watts equates to 1.75 watts of input power per ounce of all up weight. That falls nicely between the 1.5 to 2 desired. The power system is 25% of the total weight like any good FAC model.

More info in my column in the Jan 07 Flying Models.