kV and how not to burn out a motor

Electricity is by its nature more complicated than liquid fuel. The former simply has energy per litre or kilogram. Electricity has three quantities - voltage, current and resistance – all of which interact. When flying electric, one key decision is what propellor to use. I discovered to my cost (literally) how easy it is to make a mistake. I'll describe it later so you don't blunder in the same way.

However from conversations on the field I think people are still not clear about a number that they see in motor specifications. Yes, it's kV. Properly used it means kilovolts, which probably accounts for some of the confusion, because it feels as though it ought to be to do with energy or power. It is not. The symbol kV has nothing to do with either. More later.

What do we want?

Two things. First we want as much power out of our motor as we can get. Secondly we do not want to increase current so much that we break the motor. Electrical things are best run at a bit less than their rated maximum. The big difference between electric motors and IC engines is that the latter have a natural maximum power that they cannot exceed. Electric motors try to be helpful so they just keep on going like lemmings.

The science bit

Propellors are rotating wings. They have two main dimensions – diameter and pitch. Pitch is the theoretical distance the prop moves forward in one revolution. Motors make thrust by speeding up air. As the propellor pushes the air, the air pushes the propellor. Remember Newton's Third Law? 'When you push something it pushes back.' The key factors for propellors are the mass of the air speeded up and by how much and how rapidly it is speeded up. Remember F = ma? A bigger prop has a bigger area so speeds up a bigger mass. A larger pitch pushes the air further in one revolution so the air goes faster. So a big prop imposes a larger load on the motor, especially a prop with a large pitch, and the current has to rise to increase the power.

Prop geometry

A prop blade has an aerofoil. You can see it if you look at a broken blade. Not got one? Borrow one of mine or look at figure 1 later in the article. As it turns it cuts the air. When static the angle of incidence is effectively the angle of the prop blade, which is about 12°, so it is stalled and very inefficient. When moving through the air the prop's angle to the air will drop almost to zero. In theory then, if you measure the angle of the blade, simple geometry should tell you the pitch. For each revolution the tip of the propellor travels in a spiral through the air. Apparently a good propellor has about 85% efficiency.

kV – at last!

As the voltage supplied to a motor rises so does its rpm. Each motor has a rating called kV. It means the number of thousands (k) of revolutions per minute (rpm) that the motor naturally rotates at for each volt (V) you give it. It would be clearer if it was written k/V. A 500kV motor will turn at 5000 rpm on 10 V and 15000 rpm at 30 V.

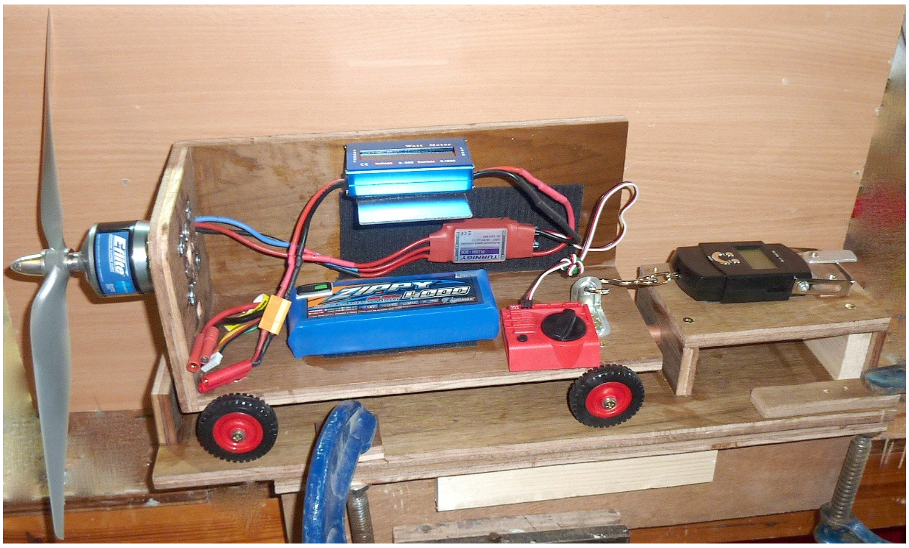
A battery with fewer cells and hence lower voltage will produce a lower speed so needs a larger prop to push the same mass of air. If you use the same large prop running at high speed on a battery with more cells it will demand more power from the motor, and hence current. This might well cause the current to rise beyond the motor's rating. So the higher the voltage the smaller the prop. That is counter-intuitive, but unlike the power limit caused by a fuel's energy density and the upper limit of oxygen going into a carburretor's throat, our batteries will supply pretty much as much current as we could ever demand.

An example will help.

Suppose we have an electric motor with a rating of 1200 kV.
On a fully charged 3S battery of about 12.6 V this turns at 12.6 x 1200 = 15120 rpm
On a 4S of 16.8 V this changes to 16.8 x 1200 = 20160 rpm
On a 6S of 25.2 V it's 30240 rpm! Now that would howl.

How did I blunder?

I have built a test rig for motors using an excellent design by Martin Phillips in the April 2016 edition of the UK Radio Control Models and Electronics magazine (Picture 1), This allows me to measure thrust against power and various other data for different motors and props. To start with I used a light detecting tachometer and the setup in the picture, though I have now switched to a FrSky receiver and Neuron ESC.



Picture 1

Photo: Peter Scott

I decided to test out a new 4Max 5065 motor. I opted for two 4S batteries in series and an 18 x 10 wood prop. All went well until I went above 1500 W. The motor speed was still around 3000 rpm but the thrust was enormous at 5.5 kg. Alarm bells should have been ringing in my brain. But they weren't and as I increased the power to 2000 W, and the thrust approached 7 kg, suddenly the motor stopped. I checked the batteries and the ESC was cool but then I noticed the smell. You probably know that burning electric smell. The motor wasn't very hot but I let it cool down and tried the throttle stick again. No, it was dead.

So what did I learn?

- With a higher voltage you need a smaller propellor, very likely smaller than you expect. The smaller area is compensated by the higher rotation speed. It is probably best to go at least one inch smaller than specified for the first try.

- Work out the maximum power the motor will stand. This will be the specified maximum current multiplied by the maximum battery voltage. Do not exceed it.
- Do a trial run gradually moving up to full throttle and watch the current reading. If it rises above the rated maximum, immediately throttle down and reduce the prop size or pitch. As you test, continue to check the current on the watt meter.
- Motors with a high kV rating are intended for lower voltage batteries with fewer cells. For example stick to 3S for kVs over 1000.
- If you are using batteries with a high cell count and voltage, use a motor with a kV in the low hundreds.

If you plan to use full throttle for much of your flight, the prop must have a diameter and pitch that results in a current maybe 10% less than the rated maximum. If you only use full throttle for a few seconds at a time you could go up to the maximum. I later calculated that at 2000 W my poor motor was drawing 76 A. The ten second maximum for the motor was 58 A so no wonder it gave up trying. The ESC was a high voltage one rated at 120/140 A. Ironically a lower current ESC might have shut down and saved the motor.

And what’s the final message?
If you decide to power a motor with a higher voltage battery, say going from 3S to 4S, fit a smaller propellor. Then the motor can turn at a higher speed. If you don’t you will waste energy through heating the motor, or at worst burn out the motor or ESC.

Propellors and load factor

Except for scale powered models, propellors are always two bladed. There is a good reason for this. The fewer the blades the better the efficiency. Apparently a single blade, balanced with a weight is best of all. However we mostly settle for two. A few scale model gliders use three bladers.

Let us look at an example. Powered scale aircraft often have three, four or more blades to reduce the diameter and improve ground clearance. I am building a DH Mosquito that has three bladers. Fortunately designer Tony Nijhuis did the sums for the one-ninth machine that I am building. However if I can fly that, I am going to build a one-fifth scale one. So of course the question is how heavy and what motors? I guess somewhere between 15 and 20 kg. I tend to build light so I think top of the range 4Max motors should be powerful enough. The specified propellor for the 4Max PO-6366-230 on 10S lipos is 20 x 10. What I needed to know was what three-blader would be equivalent.

Load factor

It turns out that you need to calculate something called ‘Load Factor’. This is a measure of the load the prop puts on the motor or engine. It isn’t a real quantity but just a number to allow comparisons.

I like Master Airscrew propellors so decided to see if their largest prop would do. Please excuse the use of ancient imperial dimensions. Props are usually specified in inches and I find propellor conversions to metric prone to error.

The formula is load factor (LF) = $d^3 \times p \times (n-1)^{-2}$
where d is diameter, p is pitch, and n is the number of blades. D and p can be imperial or metric. As you can see it won’t work for a single blade prop.

For the specified 20 x 10 two-blader:

$LF = 20^3 \times 10 \times 1$

$= 80\,000$

To give the same LF the diameter of the three-blader should be:

$(80000/(10 \times (2)^{-2}))^{-3}$

= 17.8”

The biggest three blade Master Airscrew prop is 16 x 10

$LF = 163 \times 10 \times (2)^{-2}$

$= 40960 \times 1.414$

= 58 000 (approx)

So in theory the 16” prop is too light a load. However Master Airscrew (MA) blades are wide so hopefully impose a greater load. MA don’t make a larger propellor so I will have to use it. Using my motor tester, I will test the 16 x10 on the 4Max motor using two 4S lipos in series to find the thrust, rpm and power. I want to get the thrust to around 6 kg on each motor if possible. I can go up to two 5S lipos if necessary.

Propellors unloading in the air

Intuitively we think that when a motor is turning a propellor static on the ground it uses more power than when it is flying. In fact at high speed some parts of the prop might be stalled and turbulent. The reduction in power needed when flying we normally call ‘unloading’. However I have seen no data about it. When I started using FrSky Neuron ESCs I was able to make the comparison.

To test I ran at full throttle on the ground and in the air. I put EscA (current) and EscA+ (maximum current) on the transmitter screen. This allowed me to read the actual current EscA on the ground at full throttle and maximum current EscA+ in the air. In the same way I measured RPM using EscR (rpm) and EscR+ (maximum rpm). I reset the telemetry before take-off. These were the results:

Full throttle	Static	In the air
EscA and +	55 A	48 A
EscR and +	9320	9974

Thus you see that in the air the power load the propellor is placing on the motor is about 87% of the value on the ground and rpm in the air was 7% higher .

Other data

Taxiing 12 - 20 A

Cruising at half throttle 20 - 30 A

Finding the pitch of a propellor

Two things sparked my wish to know more about propellors.

For my indoor lightweights I make prop blades that plug into a tissue-tube hub. This means that they are easily replaced but it is tricky to get both props equally set. This means the model sometimes vibrates and I am sure that I could get longer flight times with a bigger pitch. So I wanted to know how to make a jig.

The second was chatting to a club member who flies 3D behemoths with enormous props. He was talking about fitting an even larger prop than the twenty-something inch one on the model. I think he told me that the pitch would be 18 inches. I wondered why the pitch was so large.

What do you do if you have a prop with no, or indistinct, markings?

Maths

At radius r on the prop the following measurements are made:
Width of the blade W
Difference in height of leading edge h1 and trailing edge h2, measured from a flat surface.
The tangent T of the angle of attack is (h1 – h2) / W
The circumference of the path of the measurement point is found:
Circumference = 2 x Ω x r
Pitch = Circumference x T
Pitch = 2 Ω r (h1 – h2) / W

Picture 2

Picture Peter Scott

“The reason we measure pitch at 75% of the diameter is two-fold. Generally, the pitch of a propellor is not completely constant, varying somewhat from hub to tip to optimize it for the different linear speeds at each point along the blade. The pitch at 75% corresponds roughly to the average effective pitch of the propellor. Secondly, the propellor is sufficiently wide at 75% to allow one to get reasonably accurate measurements of blade width and height.

“The angle of a blade changes as you move outwards because the outer parts of the prop are travelling further (circumference) so must have a lower angle to give the same pitch.

“To put it another way, propellor blades are twisted to change the blade angle in proportion to the differences in speed of rotation along the length of the propellor and thereby keep thrust more nearly equalized along this length. If the blades had the same geometric pitch throughout their lengths, at cruise speed the portions near the hub could have negative angles of attack while the propellor tips would be stalled.” Put yet another way, ”propellors operate most efficiently when the aoa [angle of attack] at each blade station is consistent (and, for propellor efficiency, that giving the best lift drag ratio) over most of the blade, so a twist is built into the blades to achieve a more or less uniform aoa."

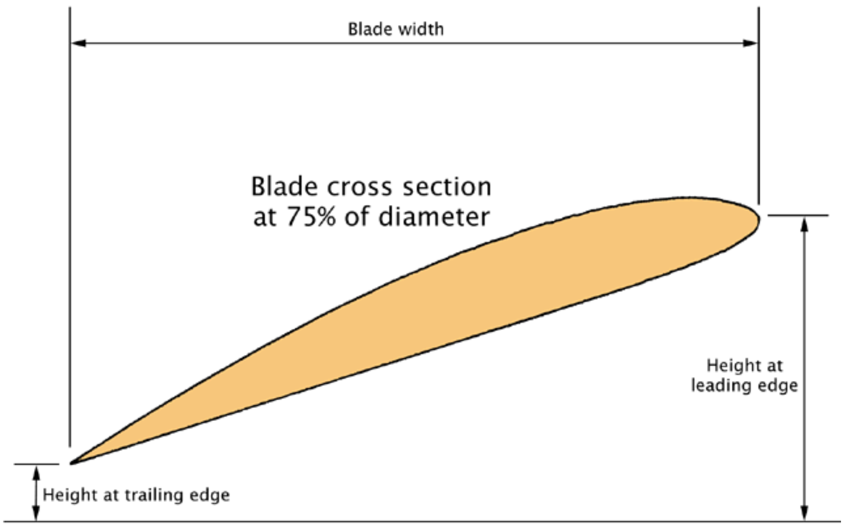


Figure 1

I gave the maths a practical test.
I used a fairly large prop to make measurement easier. (Picture 2)
I covered the markings so I couldn't know the answer.
I marked the 75% point out from the centre. Here the diameter was 380 mm.
I held the prop firmly down on a flat surface.
I measured the heights of the centres of the leading and trailing edges (Figure 1).
Rear 4.5 mm   Front 12.5 mm   Difference 8 mm
The blade width viewed from above = 36 mm
So the tangent of the blade angle is 8/36 = 0.22
So the pitch should be circumference x 0.22
Circumference = Ω x d = 3.142 x 380 = 1194 mm
Pitch = 1194 x 0.22 = 265 mm
In mediaeval units this is 10.5"
And what was the marked pitch? 10".
Considering the systematic errors in measurements (+/- 0.5 mm) this is pretty good.
QED.

So what are the answers to what started all this?

To build a jig I must decide on a prop diameter. Then I must decide on a pitch. Then I settle on a prop width at 75%. Then I calculate the angle needed. Then I make a card jig. Done!

Why was the pitch so big on the big prop? Because as the diameter goes up a prop with the same angles will automatically give a larger pitch because the circumference is bigger. A given geometry will give a 200 mm pitch on a 300 mm prop and a 400 mm pitch on a 600 mm one. The performance will be the same. So if you have a small and a large prop with exactly the same angles of attack the larger one will have a larger pitch.

On one site I had asymmetric blade factor explained. This occurs during takeoff. The propellor disk is tilted so the top is further back. This means that, as it starts to move forwards, until the tail lifts the downward moving blade has a larger angle of incidence and produces greater force. With conventional rotation this means the aircraft will turn to the left. For an explanation of the various upsetting forces due to the engine and prop (torque reaction from engine and propellor, corkscrewing effect of the slipstream, gyroscopic action of the propellor, asymmetric loading of the propellor (P factor)) go to http://www.free-online-private-pilot-ground-school.com/propeller-aerodynamics.htm

This article included quotations, which I enclosed in quote marks, from the following sites.
http://avstop.com/ac/flighttrainghandbook/basicpropellerprinciples.html
http://www.pilotfriend.com/training/flight_training/fxd_wing/props.htm
http://www.stefanv.com/rcstuff/qf200203.html

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