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Designing an Electric Power System for an R/C Plane

Very little of this information is original, but unfortunately I cannot remember many specific references that I can cite. A good book with lots of technical information about electric flight is "Electric Motor Handbook" by Robert Boucher. You can find lots of information on the internet. I use the discussion forums at http://www.rcgroups.com/forums/index.php a lot.

The following steps are designed to be followed in the indicated order; however, you typically must repeat the steps several times to fine tune your design. For example, the steps require you to know the plane's flying weight, but you may not know this the first time through the steps. The idea is to go ahead through the steps using an estimate of the weight. After you come up with a power system, you can compute the total weight. If this weight differs from your initial estimate, then you should repeat the procedure to adjust the system to match the actual flying weight.

STEP 1.

DETERMINE

- Full throttle power in watts (volts times amps)

BASED ON

- Total plane flying weight
- Flying Style

This is comparable to using cubic inch displacement of glow engines for different sized planes.

Watts/pound rule-of-thumb:

50-90 watts/lb -- trainer or basic flying
90-150 watts/lb -- aerobatics
150-200 watts/lb -- 3D ("hanging" on the prop)

Step 2.

DETERMINE

- Battery voltage
- Full throttle current
- Specific battery

BASED ON

- Full throttle power (Step 1)
- Space for battery
- Available batteries
- Flight time
- Minimize weight

The Watts (Volts x Amps) of the battery must match the selected power. There are many options. Look at the available batteries. The voltage directly depends on the battery chemistry: Lithium Polymer (LiPoly), Nickel Cadmium (NiCd), or Nickel-Metal Hydride (NiMhd) and the number of cells. Voltage is directly specified on a battery. The current capability of a battery is more subtle. Compute the full throttle current by dividing the full throttle power by the battery voltage. Then determine if the battery can provide the current and maintain the current for the desired flight time.

The current capability for LiPoly batteries is related to battery capacity. Battery capacity is measured in amp-hours (or milliamp hours). This is product of the current being produced and the time over which the current is produced. For example, the rating for a popular ThuderPower battery is 2.1 amp-hours. Theoretically, it can produce 2.1 amps for 1 hour, 4.2 amps for half an hour, or 21 amps for 6 minutes (1/10 hour). There are limits to how far you can go without problems. Too much current causes overheating, reduced battery life, and battery destruction in extreme cases. Also, you won't get the theoretical capacity of the battery if you use the current too fast.

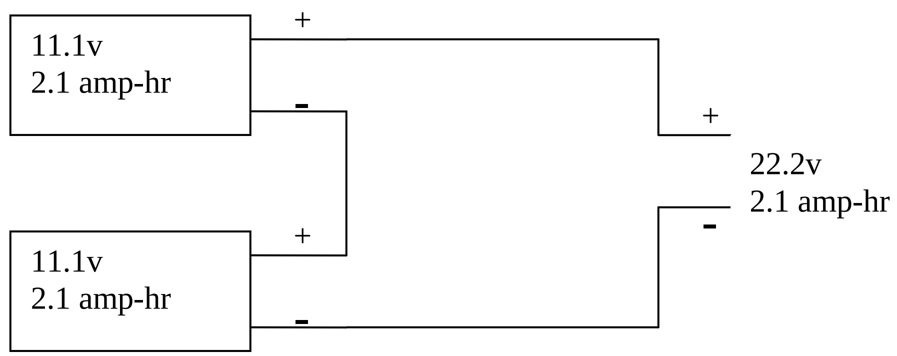
Current limits for LiPoly batteries are specified in multiples of the "C" rating, which is the number of amps that can be produced for one hour. The continuous safe-current limit for a LiPoly battery is typically in the range of 10 C to 20C. A second safe rate that applies for short bursts is also specified for most batteries. So you need to get a battery where the peak current is at least within the burst rate, and you also need to have enough amp-hours to run the motor at some average rate for the time that you want to fly. Determine the required amp-hours for flight duration by multiplying the average current by the flight time in hours. You generally won't be using full throttle the whole flight. The average current must be estimated -- generally between 50% and 80% of the full throttle current.

For example, if you want 400 watts peak, you can use 11.1 volts (a battery with 3 LiPoly cells) producing 36 amps. This means that the battery must be able to produce 36 amps without being destroyed. If the battery is rated at 15C, a 2.4 amp-hour battery is needed to safely produce 36 amps (C=2.4 amps, and 15C=36 amps). If you want to be able to fly for 10 minutes (1/6 hour) at an average of 25 amps, you need a 4.2 amp-hour battery (25amps x one sixth hr). Thus, the flying time is more of a constraint than the full throttle current. Note that LiPoly battery vendors generally over specify the C rating, so I usually avoid using the peak rating.

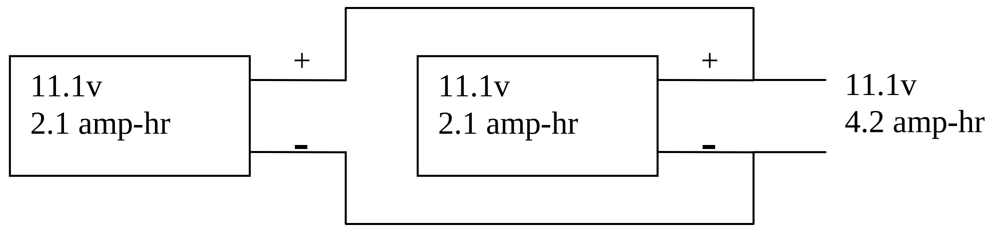
Arlen Harbaugh   6-13-2007

Combine batteries in series or parallel to get required volts, amps, and amp-hours. When combining, all of the batteries must be the same.

Series -- volts add, but current and amp-hours are the same. Most batteries already have cells in series. For example a 3S LiPoly indicates 3 cells in series. Each cell is 3.7 volts.



Parallel -- current and amp-hours add, but volts stay the same. Putting batteries in parallel is indicated by "P". 3P meanse 3 cells in parallel. 6S2P means two 6-cell series packs in parallel.



Arlen Harbaugh   6-13-2007

Step 3.

DETERMINE
- Prop
- Full throttle RPM

BASED ON
- Full throttle horizontal flying speed
- Full throttle power (Step 1)

Unfortunately, plane designs do not normally supply information about flying speed. Here are some speed ranges I have estimated:

Small electric: 40 mph
Trainer: 60 mph
3D: 40 mph
Low speed power aerobatics: 50-70 mph
Fast aerobatics: >70 mph

Select the prop diameter, pitch, and speed of rotation by trial and error using the formulas that Jim Norcutt presented at a previous meeting: prop power formula (Robert Boucher, "Electric Motor Handbook") and the pitch speed formula. That is, we want to select a prop and RPM to use the required power when the pitch speed matches the maximum flying speed.

BEFORE applying the prop power formula, multiply the total power from Step 1 by a system efficiency factor. I assume 0.8. Thus, for the 400 watt example above, the prop power is 320 watts. (The 80 watts is lost as heat in the motor and speed control).

Prop power in watts = K x diameter^4 x rpm^3 x pitch

Diameter in feet, rpm in thousands, pitch in feet
K is 1.11 for regular APC, 1.21 for APC-E

Pitch speed in mph = RPM x pitch (inches) x 60 / 12 / 5280 = RPM x pitch / 1056.

The prop selection will only be approximate. You will likely have to change the prop after the system is installed to get the exact power desired. Fortunately, you can replace the prop without losing too much money. Diameter to pitch should be between 2:1 and 1:1 -- an efficiency and availability issue. 1:1 ratio is best for high-speed flying, and 2:1 is best for low-speed thrust. Modeling lore states that for the same pitch speed and power, a large diameter low rpm prop is more efficient for flying than a small diameter high rpm prop -- I've never seen the theory to support this.

Continuing the 400 watt example (320 watts of prop power), here are some numbers from the prop and pitch speed equations:

Diam. (in)	Pitch (in)	rpm	Prop Watts	Motor Watts	Pitch mph
14	11	5500	342	427	57
14	8	6000	323	404	45
12	6	8000	310	387	45
11	5	9600	315	394	45
10	6	10500	338	422	60
9	6	12000	331	413	68
10	4	12000	336	420	45

I generated these numbers by programming a spreadsheet with the power and pitch speed equations. I selected an rpm, and then tried various prop diameter and pitch values until I obtained approximately 400 motor watts.

Step 4.

DETERMINE

- Motor (with gear drive if needed)

BASED ON

- Full throttle RPM (Step 3)
- Full throttle current (Step 2)
- Battery voltage (Step 2)
- Available motors from vendors

First, determine the motor KV, which is a theoretical constant that is rpm/volt. Take the desired full-throttle RPM and divide by the battery voltage. Then divide by 0.8 to get the motor KV. The 0.8 is necessary because the rpm will be lower than the theoretical when the motor is loaded by the prop.

In our example, if the battery is 11.1v and rpm is 8000 (12-6 prop), then the desired KV is 8000/11.1/0.8= 901.

After determining the KV, look at the available motors and find one that has the desired KV and can handle the battery voltage and full throttle current.

If you can't find a motor with a low enough KV, gearing can be used. The effective KV of the system is motor KV divided by the gear ratio; thus, you can get any KV you want. For example, if the motor KV is 3000, and you want 500, use a gear ratio of 6:1.

Current capability is often stated as two values: continuous and burst. I like to use a motor that can continuously handle the full throttle current needed. But if you expect to use full throttle only intermittently, you can use the motor's burst current rating.

Steps 3 and 4 often must be repeated by trial and error to get a good combination.

In general, inrunner motors have higher KV than outrunners. Accordingly, most outrunner motors are used without gear reduction, and most inrunner motors use gear reduction. But some applications use inrunners without gear drives. Outrunners are typically slightly less efficient than inrunners, but the gear drives used with outrunners reduce their efficiency to be closer to that of outrunners. Inrunners with gears are usually noisier than outrunners. Belt drives provide the same function as gear drives, and they are quieter than gear drives, but belt drives are less efficient.

Here are two actual motors that come close to meeting the requirements for the 400 watt example:

EFlite Power 25 BL	KV=870, 32 amps continuous, 3S to 4S
AXI 2820/12	KV=930, 37 amps, 3S to 4S

Step 5.

DETERMINE
- Electronic Speed Control (ESC)

BASED ON
- Battery voltage (Step 2)
- Full throttle current (Step 2)

Maximum voltage for the ESC must be adhered to.

Maximum current under full throttle must be adhered to even if you never plan on full throttle. An ESC produces partial throttle by using short bursts of full power. Maximum current continuously occurs for short bursts even at partial throttle. When running a system for the first time, it is a good idea to use a prop that is smaller than the prop you expect to use. Use a current meter to make sure that the system does not draw too many amps. If the prop is too large, it will draw too many amps and could burn out your speed control **AND** motor before you ever get the throttle up to full speed. It is generally OK to have an over rated ESC -- for example, a 50 amp, 20 volt ESC is fine even if your motor only needs 10 amps and 10 volts -- weight is the only penalty for a too-big ESC.

Step 6.

DETERMINE
- Receiver and servo power

BASED ON
- Battery voltage (Step 2)
- ESC (Step 5)

Three possibilities:
- Battery Eliminator Circuit (BEC) in the ESC. This uses the motor battery to provide 5v. A BEC is not integral to the ESC, but they are often provided as a convenience.
- Separate BEC connected to motor battery -- make sure that voltage and current limits are adequate
- Separate receiver battery as used in glow planes

There are limits for the BEC's in most ESC's. Here are typical limits for average non-digital servos. Digital servos and some analog servos use much more power, so the BEC may not handle as many servos.

- 4 servos if 2S LiPoly battery
- 3 servos if 3S LiPoly
- BEC in ESC usually does not work for 4S LiPoly and above.

With most ESC's that have a BEC, if you do not use the internal BEC, then you must disconnect the positive power wire from the receiver connector going to the ESC. The reason is that you don't want your receiver battery or separate BEC to be trying to supply power to the BEC in the ESC. This could damage the ESC.

Arlen Harbaugh 6-13-2007

Summary Information

Diam. (in)	Pitch (in)	rpm	Prop Watts	Motor Watts	Pitch mph	3S KV	3S amps
10	6	6500	80	100	37	732	9
8	6	8800	81	102	50	991	9
6	4	14700	80	100	56	1,655	9

Diam. (in)	Pitch (in)	rpm	Prop Watts	Motor Watts	Pitch mph	3S KV	3S amps
14	7	5000	163	204	33	563	18
10	6	8200	161	201	47	923	18
9	7	9000	163	204	60	1,014	18
8	6	11000	159	199	63	1,239	18
7	6	13200	161	201	75	1,486	18

Diam. (in)	Pitch (in)	rpm	Prop Watts	Motor Watts	Pitch mph	3S KV	3S amps
14	11	5500	342	427	57	619	38
14	8	6000	323	404	45	676	36
12	6	8000	310	387	45	901	35
11	5	9600	315	394	45	1,081	35
10	6	10500	338	422	60	1,182	38
9	6	12000	331	413	68	1,351	37
10	4	12000	336	420	45	1,351	38

Diam. (in)	Pitch (in)	rpm	Prop Watts	Motor Watts	Pitch mph	4S KV	4S amps
15	7	6500	473	592	43	549	40
14	7	7200	488	610	48	608	41
12	10	7800	479	598	74	659	40
12	8	8400	478	598	64	709	40
12	6	9300	487	608	53	785	41
10	6	11800	479	599	67	997	40

E-Flite Park 370 BL	1360 KV	12 amps continuous	15 amps burst	2S-3S
E-Flite Park 400 BL	920 KV	10 amps continuous	13 amps burst	2S-3S
E-Flite Park 450 BL	890 KV	14 amps continuous	18 amps burst	2S-3S
E-Flite Park 480 BL	1020 KV	22 amps continuous	28 amps burst	2S-3S
E-Flite Power 10 BL	1100 KV	30 amps continuous	38 amps burst	2S-3S
E-Flite Power 25 BL	870 KV	32 Amps continuous	44 amps burst	3S-4S
E-Flite Power 32 BL	770 KV	42 amps continuous	60 amps burst	3S-4S

Electricalc and Motocalc are commercially available programs that make all of these calculations.