Computer Simulation of Rubber Powered Models

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1. Introduction.

Over the years, theoretical analysis has been used to gain a better understanding of the performance of rubber powered models, as notably discussed throughout the Zaic Yearbooks (and indeed many later developments such as variable trim devices and variable pitch propellers were mooted there) and more recently the NFFS Symposium Reports and other such publications. Some of the difficulties in the early calculations were how to take into account the variation of torque as the motor unwinds and how to determine the efficiency of the propeller, which similarly changes throughout the powered phase of flight.

Computer simulation and numerical analysis provides a straightforward way to incorporate such effects and we can now provide a relatively detailed analysis of performance during the whole flight envelope. This has in turn allowed better optimization of the complete rubber-propeller-airframe flight system. Other areas still under consideration include the effects of turbulent air-flows at low Reynolds numbers, a comprehensive representation of dynamic effects, which requires a full knowledge of all lineal forces and couples acting on the model as well as the various moments of inertia, and the effects of complicating factors such as prop wash and downwash.

A number of simulations have been reported in NFFS Symposium Reports and elsewhere and I will not spend time repeating their findings here. What I will do is briefly describe the basis of the simulation, so that those with a technical interest can see where I am coming from, and then look at some interesting conclusions relating to real models. While some of these will simply confirm current experience (eg how many rubber strands are optimum for motors in models such as P30's, Coupes and F1Bs, the need to build to minimum weight and wind motors to bursting point), others might be a bit more surprising (eg the perils of delayed prop release, the limited effect of variable pitch and/or diameter) and lead to new developments (such as the return of gearing in Open Rubber models).

As is common in this field, I have used popular terminology that often mixes imperial units (inches, feet, ounces, lbs for rubber strip width, torque and energy) and metric units (for all airframe dimensions), simply for the sake of familiarity.

2. Outline of the simulation program

The simulation programs I have produced, called ffCalc2 and ffCalc3, calculate the flight performance of rubber powered model aircraft. They both reproduce quite accurately the torque characteristics of the rubber motor, the performance of the propeller and the airframe.

They can be operated at two levels. At the simplest level *(ffCalc2)*, only basic information is required: airframe dimensions, rubber dimensions (rubber length, number of strands and width) and propeller dimensions (diameter, pitch and blade-width). Defaults are provided for all other more advanced parameters. At a more advanced level *(ffCalc3)*, the user can take into account the effect of pitch and chord distributions on the propeller performance. Both programs take into account the characteristics of different batches of rubber and allow examination of the effects of basic airframe dimensions. In this way, the simulations allow optimization of the rubber motor (number of strands, length, cross section), propeller (diameter, pitch and chord distribution) and airframe (wingspan, area, aspect ratio), whether there are constraints such as weight and any other class rules (eg P30, Coupe, F1B) or not (eg Open Rubber or sport models).

They are written in Microsoft Visual Basic and all inputs and outputs are via simple "forms" on the screen. Results can also be output to a printer.

Both programs can be considered as a number of separate modules.

2.1 Input module.

This module accepts all of the airframe, rubber and propeller inputs required for the calculations. Provision is made to accept the input data in either metric or imperial units.

2.2 Airframe Module.

This module calculates some of the basic information including total drag coefficient, wing loading and Reynolds number.

2.3 Rubber Motor Module.

The rubber torque is modeled as the motor unwinds by a mathematical function (Algie 1992). While the default parameters fit Tan II, FAI Tan Super Sport and TruTorque quite well, provision is also made to calibrate the curve to fit any particular brand and batch of rubber very closely. This is accomplished through just three parameters: the maximum torque, maximum turns and torque at 50% of maximum turns. An example of the accuracy of the model is shown in Figure 1 for April 2001 Tan II rubber.

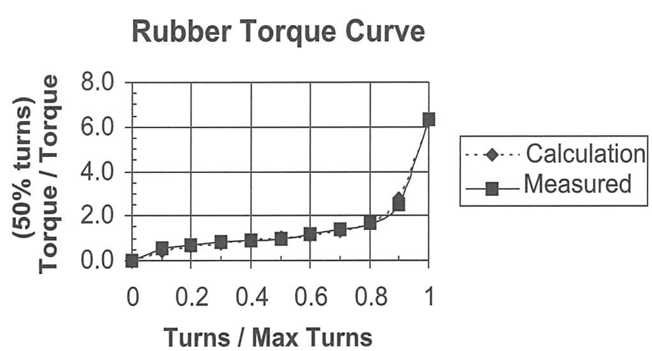

Figure 1. Rubber torque (normalised to the torque at 50% turns) as a function of the proportion of maximum turns, showing the agreement between the calculated and measured data.

The program calculates the rubber energy density (given in the traditional units of ft-lb per lb. of rubber) and the torque for each turn as the motor unwinds.

2.4 Propeller Module.

The propeller module in *ffCalc3* uses blade element theory (see eg, Glauert (1947), Houghton and Carpenter (2003)) to calculate the performance of a propeller having any particular geometry (airfoil section, pitch and chord distribution), given the torque and velocity. It determines the rpm, thrust, power, efficiency and thrust and power coefficients Ct and Cp. Also calculated are the induced and profile efficiencies, angle of attack and element of thrust for each blade element.

The method of computation is based upon that reported in an earlier NFFS Symposium by Andrew Bauer (1983).

2.4.1 Propeller airfoil.

In order to calculate the thrust and efficiencies, the program needs the propeller airfoil coefficients of lift and drag, Cl and Cd respectively, at various angles of attack (Al) and Reynolds numbers (Rn). This presents a problem since there is little data available at the low Reynolds numbers involved (typically 10,000- 70,000). In the program, Cl and Cd are modeled by equations derived by Jean Wantzenriether (1983) that give values typical of the Benedek 6405b airfoil and incorporate Reynolds number corrections. These are characterized by Cl at zero angle of attack, the slope of Cl(Al) below stall, the maximum Cl, the variation of Cd with Cl and the minimum Cd. By varying factors

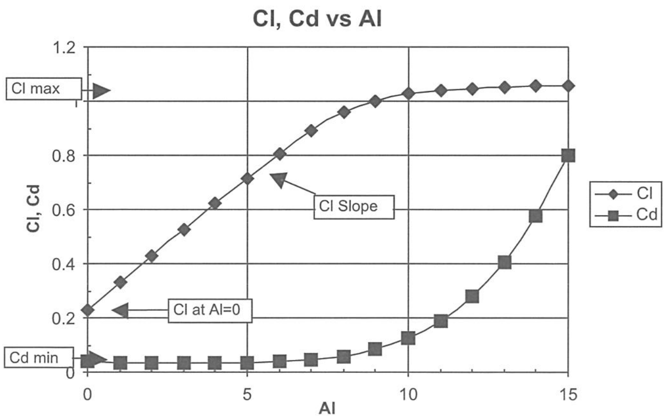

Figure 2. Model Benedek 6405b lift and drag curves as a function of angle of attack Al, showing how the four airfoil parameters are defined.

which multiply these parameters, the lift and drag curves can be modified to represent different airfoil sections, should the measured data become available. Some multipliers for other airfoils are given in Table 1.

Some curves for the Benedek 6405b section at a Reynolds number of 32,000 are shown in Figures 2 and 3.

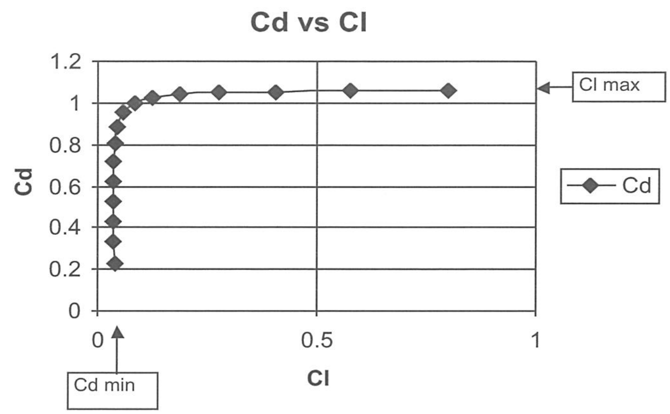

Figure 3. Model Benedek 6405b airfoil polar defining Cl max and Cd min.

Note that, for this airfoil, stall commences at angles of attack Al of about 8 or 9 degrees (Cl rolls off and Cd starts to climb steeply). The effects of radial flow along the blades (due to Coriolis and centripetal effects) have not been taken into account, as might be done in a full three-dimensional fluid dynamics analysis, for example. However, there is virtually no information about these effects in the Reynolds number range under consideration and so the values of Cl and Cd should be regarded as indicative rather than definitive.

2.4.2 Propeller geometry.

The blade geometry is represented by the propeller diameter, chord (measured in cm) and angle at nine stations equally spaced along the blade from r/R = 0.2 to r/R = 1.0. Provision is also made to modify these as a group, either by adding or subtracting a uniform amount of chord or angle, or by multiplying them by a

	Benedek 6405b	Gottingen 417a (5.8% curved plate)	Flat Plate	Davis-3R	ARA-D 6%	NACA 6405
Cl max	1.0	0.85	0.6	1.1	1	1
Cl slope	1.0	1.5	1	1	1	1
Cl at Al = zero	1.0	1.4	0	1	1.5	1.5
Cd min	1.0	1.2	1	1	1.5	1

Table 1. Airfoil parameter multipliers for some different airfoils (referenced to the Benedek 6405b parameters).

factor greater or less than unity. Also specified is the number of blades.

2.4.3 The propeller calculation.

From the geometrical parameters and the specified torque and velocity, this module calculates Cl, Cd and Al for each element of the propeller blade. These are used in turn to calculate the contributions to thrust and power per unit length, Dt and Dp respectively, which are finally summed to give the total thrust and power. Also calculated for each element are the induced and profile efficiencies Ni and Np. Ni (also called the "ideal" efficiency) is determined by the acceleration of the air through the propeller disk and Np by the drag of the airfoil section. The total efficiency is the product of the two. By examining the variation of these parameters along the blade it is possible to optimize the blade design. The calculation also yields the propeller rpm.

The other version of the program (*ffCalc2*) uses a parametric description of the propeller via the thrust and power coefficients Ct and Cp as functions of advance ratio J. This simplifies the input data requirements to just diameter, pitch and blade-width and manages reasonably well conditions of deep propeller stall where the blade element model sometimes runs into difficulties. Results are very close to the full blade element calculation for normal flight conditions. (See Rossiter (2003a) for a full description of this version). Finally, a separate module called *PropCalc* has been written to allow examination of propeller performance under particular torque and velocity conditions.

2.5 Aerodynamic Module.

This module takes thrust data from the propeller module and uses it to calculate the flight path of the model (velocity and angle) for each revolution of the propeller and during glide. This is accomplished by resolving the forces acting (gravity, thrust, lift and drag) in the horizontal and vertical directions. The basic equations have been presented in a number of aero modeling texts (see eg Symons (1999), Kaynes (2001)) and of course form the very basis of aeronautical engineering (see eg , Etkin and Reid (1996)).

Because of difficulties in determining the flight dynamics of a model, largely due to the effort involved in finding accurate values for the many and various forces acting and actual moments of inertia (see eg Bauer (1986), King (2003)), the module simply assumes that surfaces are trimmed for zero Cl during the rapid vertical climb phase where thrust exceeds weight and then set at the specified glide configuration for the cruise and glide. The program then finds the optimum (2d) flight trajectory through a process of iteration. Spiral climbs and stability effects are thus not taken into consideration in this particular calculation.

Factors such as DPR delay, launch velocity and gearing are included in the parametric propeller model. The initial launch height is assumed to be 2 meters.

A slight complication occurs when the thrust is insufficient to sustain climb and ultimately the propeller simply windmills while the model glides. This descending cruise phase is also modeled through the aerodynamic equations, but with a commensurate increase in the drag coefficient when windmilling occurs. The program calculates the proportion of motor run in this non-climbing cruise mode.

2.6 Bringing it all together.

The computational problem is that the propeller coefficients depend upon rpm and velocity, but these in turn determine the thrust, which in turn determines the velocity and so we are back where we started. The solution is to solve the equations using repeated iteration until a steady state solution is found.

The first stage of the calculation uses the rubber torque to calculate the propeller rpm and thrust at each turn using an equation (which takes into account the propeller diameter, pitch and blade width) derived from the basic Abbott propeller power equation. This is used to determine a first approximation for the climb angle and velocity, which is fed into the propeller module to determine the next approximation of the rpm and thrust. This information is then fed back into the aerodynamic module to get the next approximation for angle and velocity, and so on until a stationary solution is found.

The output from all of this is the velocity, climb (or glide) angle and duration for each unwinding turn of the rubber motor. These give the climb height and time per turn of the propeller, which are then summed for the total number of turns giving the total climb height and duration. Different equations are then used to determine the glide duration and hence the total flight duration.

Note that the programs do not require any arbitrary "correction factors" to bring results into agreement with observed behavior.

3. Some Interesting Findings.

3.1 Matching motor and propeller to airframe.

Systematic variation of motor and propeller input data for any particular model shows that, whatever the nature of the model (eg wing area, wingspan, total weight, motor weight etc), there will always be one (and only one) optimum motor/propeller configuration that will produce the longest flight times.

Let us look at results for some typical models to see how the information can be used. The outcome for any particular model will of course depend upon the actual model and rubber parameters used.

3.1.1 P30 (Czech propeller).

Examination of the Czech propeller blade element data (assuming a Gottingen 417a curved plate airfoil, flattened to about 3% camber and including Reynolds number effects) shows that the inner half of the propeller is in fact badly stalled at the end of the initial climb when the velocity drops (the propeller efficiency here is very low at 30 – 40%).

Appropriate values of Cd and Cl for the airframe can be found in the papers by O'Dwyer (2001) and Evatt (2003) in which a number of different P30 models were flight and glide tested. For my P30, the appropriate values are Cl = 0.9 – 1.0 and Cd = 0.04 for the wing, and a total drag coefficient of 0.17.

With these parameters and rubber parameters matched for a particular batch of Tan II, the results for a typical P30 model (45g airframe weight, Czech propeller) with 10 gram motors having different numbers of 1/8" strands are shown in Table 2.

One very interesting result is that going from 6 to 5 to 4 strands of 1/8" Tan II progressively reduces the detrimental effect of propeller blade stalling and this will contribute to better flight times. However, in the case of 4 strands the flight times are particularly sensitive to the torque characteristics of the actual rubber used. If the torque is insufficient to leave the model at some altitude (eg greater than 10 meters) at the end of the motor run, the 5 strand motor will be best. If the height at the end of the motor run is greater than 10 meters (as will be the case with good rubber and a model built to minimum weight) then the longer run with some extra glide will give a better total flight time for 4 strands. In the last few National Championships in Australia, all of the top models used 4 strands of 1/8" Tan II.

Strands of 1/8" Tan II	Height at end of motor run (m)	Total flight duration (sec)
4	12	116
5	45	115
6	47	99

Table 2. Height at end of motor run and total flight duration for a P30 model having various numbers of strands of 1/8" Tan II.

3.1.2 Coupe

For a typical Coupe (109 cms wing span, 70g weight and 47.5 x 56 x 3.3cms propeller) and Tan Super Sport rubber parameters, the flight times for 10g motors with varying numbers of 1/8" strands (wound to breaking point) are shown in Table 3.

Strands of 1/8" Tan Super Sport	Height at end of motor run (m)	Total flight duration (sec)
8	35	225
10	50	234
12	54	225
14	54	210

Table 3. Height at end of motor run and total flight duration for a Coupe model having various numbers of strands of 1/8" Tan II.

Here it appears that 10 strands might give a small still-air advantage over 12 strands. (However, I currently use 12 strands to help the model climb more quickly above ground turbulence). It is interesting to note that quite long still air times are predicted for a minimum weight Coupe. Perhaps not many of our current models have been truly optimised?

3.1.3 F1B.

The simulation for an Andriukov F1B propeller (running with optimum fixed pitch) shows that only near the top of the steep climb do the elements of the inner half of the propeller approach stall (Al > 8 degrees and correspondingly low values of efficiency). At launch (assuming a good launch velocity) and in cruise, the whole propeller is generally working quite well. Nevertheless, the program clearly shows that further performance gains are possible by varying the pitch and/or diameter during the powered phase of the flight, thereby maximizing efficiencies and thrust for each torque value (see below).

Since the blades operate at quite small angles of attack for much of the time (2 – 4 degrees), it is very important that the angle of the blades is set very accurately and certainly with no more than about 0.5 degree difference. This will require very accurate jigging to get it right.

For this propeller and a typical F1B airframe, the total flight times for 30g motors with different numbers of 1/8" strands of Tan Super Sport (Jan 2003) are shown in Table 4. For this particular configuration it can be seen that 22 -24 strands is probably optimum for still air.

It is interesting to note that these durations are down considerably on the best predicted still-air flight times with Tan II of around 310 seconds (see below).

Peter King (2003) recently reported the advantage of a 24 strand motor over 26 strands in a F1B (and 12 strands over 14 strands in a Coupe).

3.1.4 Open Rubber.

Let us consider here the effects of varying the number of motor strands for a given motor length and no restriction on motor weight. Results in Table 5 show that for a motor length of 85.5 cm in a 260 sq in Open

Strands of 1/8" Tan Super Sport	Height at end of motor run (m)	Total flight duration (sec)
20	65	237
22	69	236
24	71	233
26	72	229

Table 4. Height at end of motor run and total flight duration for a F1B model having various numbers of strands of 1/8" January 2003 Tan Super Sport.

Rubber model with a 60 cm x 72 cm x 4.2 cm propeller, airframe weight of 125 gm and good Tan II rubber, the best duration of about 550 seconds will be given by a motor of around 75 gm (i.e. 18 strands of 3/16" Tan II). By way of comparison, the Open Rubber model upon which this simulation was based won the 2003 Southern Cross Cup event with a very late afternoon (i.e. dusk) flight of 576 seconds using just this motor configuration.

The effects of different propeller diameter, pitch and blade width can similarly be investigated and again

Strands of 3/16" Tan II	Height at end of motor run (m)	Total flight duration (sec)
16	159	538
18	174	553
22	190	552
24	196	549
26	199	542

Table 5. Height at end of motor run and total flight duration for an Open Rubber model having various numbers of strands of 3/16" Tan II.

matched to any particular motor. Similarly some basic changes to the airframe weight and dimensions (eg wingspan and aspect ratio) are also easily investigated.

If all restrictions on motor cross section, motor length and the propeller diameter are relaxed (but keeping the pitch at 1.2 x diameter and blade width 0.1 x diameter) and if Jan 2003 Tan Super Sport rubber is used, the simulation shows that a flight time of 674 seconds is possible from a motor with a weight of approximately 250 gm (configured as 18 strands of 3/16" Tan II, 295 cm long) and a 45 x 54 x 4.5cm propeller. Note that this is a genuine optimum configuration for this model and rubber and all other configurations (prop diameter, motor cross section and length) will give shorter flight times.

A summary of the results is given in Tables 6 and 7. Table 6 shows the effect of propeller diameter (motor length and cross section having been optimized for each case), while Table 7 shows the effect of varying motor cross section, using the optimum 45cm diameter propeller.

These results support the statement that for any airframe there is indeed one and only one overall

Propeller diameter (cm)	Flight time (sec)
65	627
60	649
55	662
50	671
45	673
40	670
35	650

Table 6. Effect of propeller diameter on total flight duration of an Open Rubber model.

Motor cross section (strands of 3/16" Tan II)	Flight time (sec)	Optimum motor length (cm)	Rubber weight (g)
14	662	320	213
16	673	310	235
18	674	295	250
20	668	290	275

Table 7. Optimum motor lengths, motor weights and flight times of an Open Rubber model for various rubber motor cross-sections.

optimum configuration (and this holds true whether or not there are any restrictions on motor length or weight or on the propeller). It also supports the notion that the motor weight should be 2/3 of the total weight for longest flight times, assuming a fixed airframe weight (see eg Pressnell (1986), Meuser (1992)), and this holds for non-optimum propellers as well as the optimum configuration (though the above results do not take into account the fact that fuselage weight will probably depend to some degree on the maximum motor torque that it will have to withstand).

As the optimum motor is nearly 3 meters long (!), there might be a case for gearing in Open Rubber models (see below).

3.2 Delayed (DPR) or Instant (IPR) Prop Release?

Using a similar computer simulation, Ian Kaynes (2001) considered the effect of different launch velocities on the ultimate height attained of a typical F1B model. He showed that an increase in launch velocity from 4 to 12 m/sec resulted in an extra 7m of height. His simulation assumed a DPR of 0.2 seconds.

But is there any benefit of DPR compared to IPR?

Let us consider again a typical F1B model and compare the height obtained with delayed and instant prop release launches. Taking firstly the DPR case, if the model is launched vertically at 8 m/sec, at the end of the 0.2 second DPR period the velocity will have dropped to 5.7 m/sec (due to drag and gravity) and the model will have gained 1.36 meters above the launch height. The propeller will then start and the model will accelerate to a maximum velocity of about 12.5 m/sec before it starts to slow down again as the motor unwinds and the torque falls (assuming 24 x 1/8" strands of Tan Super Sport).

If a model with IPR is launched vertically at the same 8 m/sec velocity, by the end of the 0.2 second period it will have climbed 1.89 meters above the launch height and will have accelerated to a velocity of 10.9 m/sec. However, height gained under DPR is just sufficient to offset the higher velocity gained under IPR and the DPR model will retain a small height advantage of around 0.4 m.

If however, the DPR delay time is set at 0.6 seconds, the larger velocity gained under IPR is critical and much more important than the 2.8 meters extra height that would be gained with DPR. Running the simulation to longer times shows that the extra velocity results in the IPR model now climbing about 3.2 meters above the DPR model and retaining that height advantage for the rest of the flight. The full results are given in Tables 8 – 10.

It is thus clear that the accuracy in setting the DPR is critical, particularly if the launch velocity is less than about 10 m/sec, as is probably generally the case. I cannot guarantee the DPR on my mechanical timer to more than +/- 0.2 sec and so have no chance! If ever there was an argument for electronic timers in F1B this is it. Furthermore, since the critical DPR time depends

Launch velocity (m/sec)	Gain of DPR (0.2 sec) over IPR. (m)
4	-0.7
8	+0.4
12	+1.2
16	+2.0
20	+2.6

Table 8. Height gain from DPR over IPR for a propeller release delay of 0.2 seconds.

Launch velocity (m/sec)	Gain of DPR (0.4 sec) over IPR. (m)
4	-2.2
8	+0.3
12	+2
16	+3.4
20	+4.6

Table 9. Height gain from DPR over IPR for a propeller release delay of 0.4 seconds.

Launch velocity (m/sec)	Gain of DPR (0.6 sec) over IPR. (m)
4	-9.2
8	-3.2
12	-0.5
16	+1.6
20	+3.3

Table 10. Height gain from DPR over IPR for a propeller release delay of 0.6 seconds.

upon the launch velocity, a high degree of launch reproducibility will also be important.

Note that for launch velocities less than about 7 m/sec, there is always a disadvantage in DPR, but some useful benefits if the launch velocity is greater than about 12 m/sec. Can this be accomplished? The test is to see how high you could throw the model vertically without any assistance from the rubber: a 12 m/sec launch would result in the center of gravity of the model reaching a height of 6 m above launch height. Experience suggests that most fliers might only be able to achieve a height up to around 3 meters, while world class fliers might just get up to the six meters (*Walt Ghio, private communication*).

This finding supports the conclusion of Dave Lacey (1993) that "..if you can really heave the model, small gains in altitude can be obtained if the prop is released at the optimum velocity". However, he did not pick up that there is actually a disadvantage in DPR if the launch velocity is below around 7 m/sec and the critical nature of the actual DPR delay.

This is in some way a corollary to the Ian Kayne's result cited above: that it is critical to launch an F1B model at the highest velocity possible, whether DPR or IPR, and ideally no less than the equilibrium flight velocity, since it results in a real height gain. Failure to do so can result in a loss of height up to around 10 meters.

3.3 How beneficial is variable pitch and/or variable diameter?

There are arguments for varying either the pitch or the diameter (or both) to better match the propeller to the varying torque of the rubber and the variation in advance ratio J during the flight. For maximum effect, the pitch variation should vary in the same manner as the J curve (see eg Krol (1973)). Similarly, one might expect that there could be some benefit to be gained by varying the propeller pitch and/or diameter to make better use of the high initial torque of the rubber motor at launch.

The changes in advance ratio J and propeller efficiency of a F1B model as the motor unwinds are shown in Figures 4 and 5 for a 24 strand 1/8" Tan Super Sport motor and a 62 x 75 x 4.1 cm prop (using the parametric prop module). The DPR data correspond to the propeller starting at a model velocity of 8 m/sec.

The variation of propeller efficiency with advance ratio for this particular propeller is shown in Figure 6 over the range of operating conditions corresponding to Figures 4 and 5.

One could thus imagine that there might be a great application here for an electronic timer to continuously vary the prop pitch and/or diameter in some specific way as the motor unwinds. This would allow a

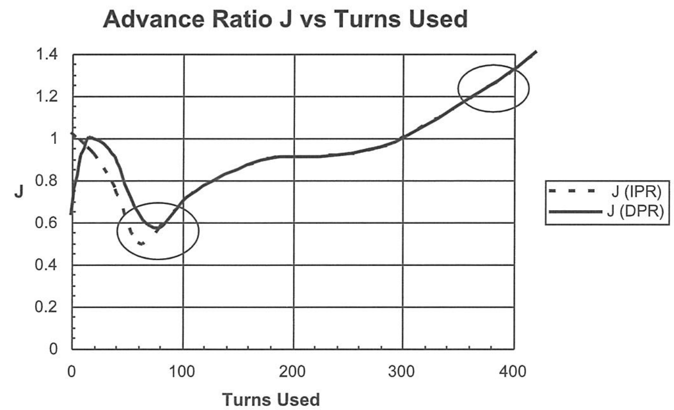

Figure 4. Variation of advance ratio J with the number of turns used for an F1B model with either DPR or IPR.

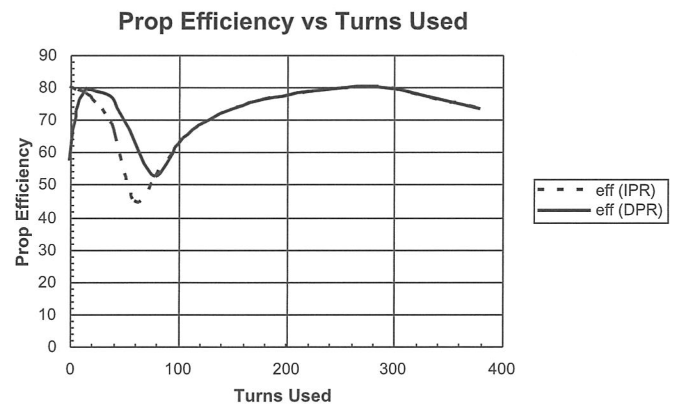

Figure 5. Variation of propeller efficiency with the number of turns used for an F1B model with either DPR or IPR.

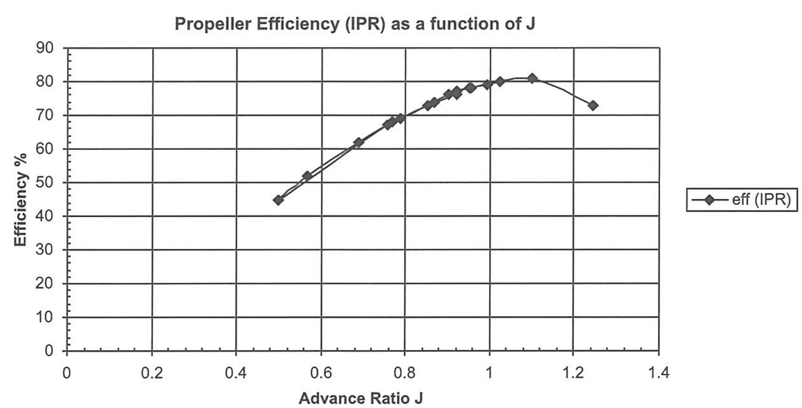

Figure 6. Propeller efficiency as a function of advance ratio J for the F1B propeller used in the above examples over the range of operating conditions corresponding to Figures 4 and 5.

much better match to the required variation than the mechanical methods currently in use. However, before getting too carried away, it is worth investigating the maximum likely benefits. This is easy using the simulation, where any arbitrary variation in pitch and diameter is possible as the motor unwinds. Unfortunately, in practice the pitch can only be varied by twisting the whole propeller blade through some angle. Similarly, the diameter can only be varied by moving the whole blade in or out from the hub. Both of these have the undesirable effect of moving away from the desired helical (or nearly helical) pitch distribution along the blade. This means that, whether the blade is twisted or moved in or out (or both) a smaller proportion of the blade is working at the optimum angle of attack for the prevailing conditions. Variations in diameter are thus limited to no more than about +/- 10 cm or blade angle to no more than +/- 10 degrees. (Note that this effect becomes less important at larger diameters where the blade angle varies more slowly with radius, and hence the extensive use of "variable pitch" in full-sized propellers). It is of course necessary to use the full blade element propeller simulation so that such effects are properly taken into account.

Various combinations of blade angle and/or diameter that varied with J and/or torque were tried, but the benefits were generally much less than expected. The best I could manage was an extra 2 meters of height and around 5 extra seconds of flight time using both a diameter and angle that varied with J (-3 cm and -5 degree from nominal), or an angle that varied with both J and torque (+/- 5 degree). While such arrangements produced a higher climb during the burst (with an additional height gain of up to 4-5 meters in 30 meters), around 20% more turns were used during this phase (mainly towards the top of the vertical climb) resulting in the smaller total overall height gain and corresponding duration.

One interesting result is that, assuming a reasonably fast launch, the optimum diameter at the start of the motor run (i.e. high torque) is essentially the same as that required for the cruise phase where torque is much less. This is because J is similar for both conditions. The only beneficial change is a reduction in diameter towards the top of the vertical climb where J dips significantly, but this is again largely offset by more turns being used.

Varying pitch alone with torque (as mechanical VP hubs currently do) in the simulation only produced at best a one meter gain in overall height and a couple of seconds of additional flight time.

Better gains were possible by making changes in pitch and diameter of a propeller whilst maintaining a helical pitch distribution, but such a propeller could not be implemented in practice.

3.4 Critical effect of weight.

The importance of weight on flight time is demonstrated in Table 11 (same P30 model as considered in Section 3.1.1: 4 strands of 1/8" Tan II).

Running this simulation for a number of different P30 designs shows that each gram of weight over 40 gm results in the loss of between 2 and 3 seconds total flight time. For Coupes it is a loss of about 2 seconds per gram above minimum weight, and 1.5 seconds per gram for F1Bs. These results are in excellent agreement with theoretical predictions (see eg Carson (1987), Boteler (1978), Pressnell (2004)).

Airframe weight (gm)	Flight time (sec)
40	127
45	116
50	107

Table 11. Effect of airframe weight on total flight time for a P30 model with 4 strands of 1/8" Tan II.

3.5 The need to wind to breaking point.

The critical importance of fully winding the motor in a competition model is demonstrated in Table 12 (F1B model with 24 strands of 1/8" March 2002 Tan II).

The last five turns are worth around 4 meters in climb height (assuming a fast launch), but beware the sixth turn!!

Turns	Height (m)	Flight Time (secs)	Torque (N-m)
400	86	264	0.39
405	89	272	0.43
410	92	280	0.47
415	95	288	0.52
420	98	296	0.58
425	101	305	0.64
428	104	312	0.70
429	Broken!!!	0	0

Table 12. Critical dependence of height at end of motor run and total flight time on the number of turns (and torque) for a F1B model with 24 strands of 1/8" March 2002 Tan II.

For a sport model, winding a properly lubricated motor to no more than about 85% of the maximum turns will be a good compromise between possibility of a broken motor (and stress during winding!) and good flight duration.

3.6 Is there any benefit in gearing?

There have been many reports over the years describing the use of gearboxes or other such devices in rubber powered models. Unlike their electric or internal combustion counterparts, which use reduction gearboxes to great effect, with rubber motors they have invariably been either step-up ratios, such that the propeller turns faster than the rate at which the rubber motor unwinds and which reduce the torque available at the propeller but increase the runtime by reducing the rate at which the motor unwinds (again giving the effect of a longer, thinner motor), or 1:1 arrangements used to double the effective length of a motor..

Such arrangements have also been used to allow shorter motor lengths for scale models or to achieve better model balance (and reduce strength and weight requirements at the rear). Variable ratios have been considered and they have even been used in fragile indoor models. Gearless transmissions using ingenious configurations of rods and cranks (also known as "warp drives") have also been described. Gears can also be used to enable contra-rotating propellers and reduce twisting in lightly-built fuselages.

Some of these arrangements are discussed in more detail in Don Ross' book (1998), which also provides a useful list of references for the historically minded. Croome (2004) has also recently revisited the use of "return" gears in vintage Wakefields and also speculated on some future applications.

I have presented elsewhere (Rossiter 2003b) a full analysis of geared rubber motors in and give here only a summary of the findings:

1. Whatever the nature of the model (eg wing area, wingspan, total weight, motor weight etc), there will always be an optimum motor/propeller configuration that will produce the longest flight times (as discussed above).

2. Introduction of a gearbox will always reduce the overall system efficiency compared to the optimum direct drive situation and so will always reduce flight times.

3. For a given rubber weight (but variable number of strands and hence length), the optimum propeller design for direct drive will also be the optimum design for any geared configuration. All an ideal gearbox can do is restore the same optimum efficiency for a different motor configuration. Any real gearbox will introduce extra losses and so will reduce flight times.

4. For a fixed motor length (but variable number of strands and hence weight), the best propeller geometry will of course be different for each configuration. However, there will again be one optimum configuration, which will produce the longest flight times. Once again, there will be no benefit from gearing.

5. Gearing will only be of benefit if the optimum direct drive motor length is greater than about 150% of the fuselage length (or even greater if the gearbox efficiency is less than 80%). As noted above, this might be worth investigating for Open Rubber models.

6. For a fixed propeller size (eg P30), the longest flight time is always obtained with direct drive, provided that the motor with the optimum number of strands can be accommodated within the fuselage. This flight time can only be matched at best by a geared configuration if the gearbox has 100% efficiency, which is never possible in practice.

7. Where a gearbox is to be used because of fixed motor length limitations (eg some scale models), for a fixed propeller size and gearbox efficiency, the maximum flight time does not depend upon the actual gear ratio, provided that motors having different numbers of strands can be accommodated and matched to the gear ratio. However, this will never be as good as the direct drive configuration. Furthermore, the optimum propeller for direct drive will again be the optimum for a geared configuration, whatever the gear ratio.

3.7 Effect of sink and lift.

Peter King (2001) and Martyn Pressnell (2004) have shown that relatively small amounts of sink or lift can produce a large effect on flight times, particularly during the glide phase. For this reason, it is probably prudent to err slightly on the side of the motor configuration that produces the greatest height to maximize the chance of picking up the benefits of any lift (eg possibly 24 rather than 22 strands of 1/8" Tan II or 26 strands of 1/8" Tru Torque or Tan Super Sport for F1B, or maybe 11 or 12 strands of Tan II for a Coupe).

4. Conclusion.

Computer simulation can now provide some clear guidance for how to improve the performance of rubber powered models and save a lot of time in reducing "trial and error" out in the field.

One particular advantage is that a simulation can give either a snapshot of what is happening at any instant (eg torque, propeller efficiency, thrust, climb angle, velocity) or an overall result (climb height or duration).

The final performance of any model will of course always depend upon the ability to design effectively, to build light and strong, to trim a model for optimum performance, to launch properly and to pick good air on the day, thereby taking into account a plethora of effects many of which will probably never be incorporated into the simulations. That we still have to rely on the human component is indeed a blessing, and one that gives the hobby its unquenchable attraction!

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The programs *ffCalc2*, *ffCalc3* and *PropCalc* are available on CD ROM from the author at a small cost to cover media, packing and postage. In the interests of keeping them simple to operate, these versions do not currently include the DPR, variable pitch or variable diameter facilities, though they may be made available in subsequent updates if there is sufficient interest. For further details, contact Paul Rossiter at: kathymay@ozemail.com.au.