ENERGY STORAGE IN RUBBER FILAMENTS

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INTRODUCTION

The rubber motor is the most important and least understood component of the indoor model aircraft. Selection of the optimum motor is difficult for several reasons. Rubber is not a prime mover; it is solely a means of storing, temporarily, mechanical energy, and paying it out again in a metered fashion. One would like this means of storage to be predictable and consistent, but temperature, age, batch, cross section, and even length of time the energy is stored all contribute to output irregularities. The indoor builder can evaluate the structural components of his model reasonably easily by feel and sight, but there is no way to "feel" or to "see" energy storage. The only way to ascertain the stored energy available under a given set of conditions is to measure the output, a process which, unfortunately, must be done in indirect fashion. In some way a graph of the torque-twist relationship must be obtained, the area under such a curve representing the output available. A simple torquemeter may be employed to obtain sufficient simultaneous measurements of torque and turns to enable plotting the required graph for the given conditions. This method has been used for many years -- an occasional graph appears in the literature -- but the method is obviously not adapted to the necessary large scale testing.

The most satisfactory method of evaluating the mechanical properties of indoor motors would be a torquemeter capable of plotting a continuous torque-turns curve for an unwinding motor. The author has constructed such a unit, a portable, automatic recording, torquemeter. A sheet of graph paper is mounted on the plotter mechanism, and a motor is wound and unwound at the desired speed. After the motor is unwound, a precise torque vs. turns graph, accurately scaled, exists. Scaling, which can be varied, has been standardized at 200 turns per in. (X-axis), and 0.1 in-oz per in. (Y-axis), as providing adequate curves on handleable sized graph paper. Figure 4 shows one family of curves, traced directly from the machine made graphs. The advantages of such a machine are not all completely obvious; Temperature affects rubber, yet the difficulties of recording data and handling manually operated equipment at, or near, freezing temperatures (bare hands!) precludes much of such testing. The resulting data are of no direct use but they are invaluable in shaping the curves of the graphs that are of use. Additionally, the X-drive of the plotter can be operated independently of the turns mechanism to assist in evaluating energy losses as a function of time.

Figure 1 shows in general the form of the winding and unwinding torque curves for a rubber motor of a given length. The uppermost curve represents the winding-up torque characteristic. If we stop winding at various points along this single curve and plot the torque as the motor unwinds we obtain a family of S-shaped curves pendant from the winding curve. It is the precise shape of these latter curves that is of particular interest (and concern) to us because the shape describes the nature and extent of the power burst, and the ability of the motor to provide a sustained, reasonably uniform torque. Furthermore, since the area under the unwinding curve represents the total energy available for the degree of winding done, we are interested in a comparison of this area to the weight of rubber required to obtain the curve. Unfortunately, we can not dictate either the shape of the curves or the area under them; we simply use whatever rubber is available, powering our models with larger, or smaller, rubber cross sections, or longer, or shorter, lengths of motor as our intuitions tell us. "Having the book" on a given rubber is, however, an enormous boon to the intuition: the

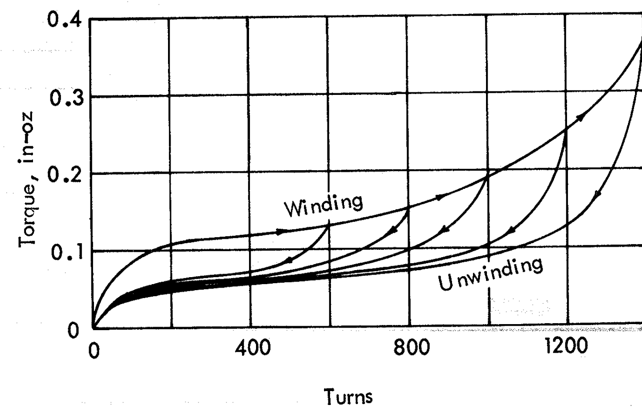

Figure 1. Hysteresis: 10 x .04 Pirelli, first wind-up.

shapes of the unwinding curves are exact; if several identical motors are handled in a similar fashion their unwinding curves will be nearly identical. It is, then, no surprise that the most successful builders maintain notebooks of power plant data: propeller used, size and length of motor, turns wound in and let off, flight time. It is, in part, this information which makes them successful, not that they record the information because they are successful.

TEST PROCEDURE

Testing by builders, even today, is sporadic and uncoordinated; no standards exist for such work. Gathering discrete data values by removing small increments of turns from a motor connected to a simple torquemeter is an arduous task. Efforts, under these conditions, are directed towards maximum values for comparison of various rubbers. To be of greatest service, however, a comprehensive test program should cover the range of use of the material. Motors are not consistently maximum wound. To ascertain the effects of temperature, and of holding tightly wound motors, easily duplicatable control variables are needed.

Some thirty years ago the author made a rather comprehensive series of tests of the highly regarded Brown rubber using a beam-balance type of torquemeter. With the loss of availability of the material the data and results became of only academic and historical interest. At that time much thought was given to the most satisfactory test program. It seemed best, for obvious reasons, to avoid as a control variable any measured property of the material itself, such as torque. The procedure that, it was felt, would be most satisfactory would be to wind motors always to the same number of turns per in. Thus, by starting at a low value for this control variable the turns per in. could be increased in any desired increments for fresh motors. To place results onto a satisfactory footing for comparison, all output work figures would be converted to output in in-oz of work per oz of rubber; the "specific energy." To avoid ungainly equipment and excessive wastage of rubber needed for motors, only a 10-in. motor base was used on the torquemeter employed for these tests.

For the most part, to obtain sets of value, groups of three motors -- 10, 12, and 14-in. long -- all from a single skein of 3/32-in. Brown rubber, were tested at fixed numbers of turns per in. -- one group at 30 turns per in., one at 40 and so on -- through 120 turns per in. Primary testing was at room temperature but some testing was done at freezing temperatures and some at slightly elevated temperatures.

Because this mode of testing produced results both substantial and consistent, the work being done at present with the recording torquemeter has been planned to parallel that early testing. Similar groups of motors, 10, 12, and 14-in. long, are being tested on the same length of motor base, 10-in., as used before. Varying degrees of winding, primarily 60, 80, 100, 120, and 140 turns per in., are being used at varying temperatures. The rubber under investigation is 0.040-in. Pirelli, 1959 vintage, from stock which has been maintained deep-frozen since obtained from the manufacturer.

TORQUE-OUTPUT WORK

In the initial studies on Brown rubber it appeared that a potentially useful relationship existed between the torque to which a motor was wound and the work available from the motor under those conditions. It now appears that a similar relationship exists for the Pirelli rubber tested. The left curve of the graph of Figure 2 shows this relationship between the maximum torque and specific energy for the second and third wind-ups of 0.040-in. Pirelli. A brief explanation of the curve is in order; a 0.040-in. Pirelli motor is wound to any desired amount, i.e., to half turns, to capacity, to 73 turns per in. After the winding is completed the torque is measured. This torque is the "maximum" torque of the graph. By finding this value on the graphed curve the specific energy for that wind-up can be read immediately from the Y-axis. If this specific energy is multiplied by the motor weight the result is the exact total work available from that motor for the winding done. This work available is a fixed amount for the torque to which the motor is wound; for a given motor it is independent of the style of winding. The importance to serious flying is clear. Incidentally, not all of the available data have been plotted in Figure 2. Much overlap of plotted points occurs so that some of the overlapping values were omitted for clarity's sake.

The length of motor, within test limits, seems to have little or no effect upon this relationship. It was impossible to distinguish between the plots of specific energy for each length of motor sufficiently to draw three separate curves. The effect of filament

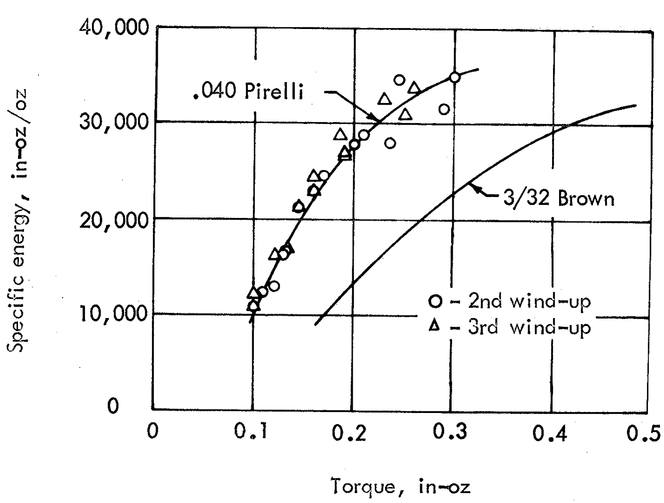

Figure 2. Output: 10, 12, and 14-in. motors.

cross section on the specific energy has not been determined; however, the right hand line of the graph shows the curve obtained years ago for the 3/32-in. Brown rubber, a curve similar to that for the smaller cross-sectioned Pirelli. Hence we can begin to speculate that other sizes, and other types, of rubber would have similar curves. It may be necessary only to make a few tests to establish positions of these curves, a possible field for additional investigation. Further testing to establish curve positions for a multiplicity of wind-ups is desirable -- will the tenth wind-up agree with the second and third?

SLACK

Builders have long felt that slack, that is, motor length in excess of the distance between hooks, has a deleterious effect upon the motor output. Increasing the length of the motor, it is felt, does not increase the available output in proportion to the added length. The Brown rubber tests of many years ago, however, showed a completely negative response to slack ranging from -50% to +100% [motors from 5 in. to 20 in. in length on a 10-in. base, using the standard formula for percent slack: 100 x (motor length - base length) / base length] as the following table of output torque vs. turns indicates. The torques at varying percents of initial turns for motors of varying lengths exhibit variations, but these variations are slight and inconsistent and not directly length related.

OUTPUT TORQUE
3/32-in. Brown Rubber
Third Wind-Up
100 turns per inch

Length of Motor, in.	% Initial Turns Remaining in Motor 25%	50%	75%	100%
	Torque, in-oz			
5	0.105	0.135	0.200	0.530
10	0.095	0.145	0.190	0.540
12	0.095	0.140	0.145	0.530
14	0.100	0.145	0.180	0.525
16	0.105	0.135	0.175	0.530
20	0.100	0.125	0.160	0.560

Work thus far upon Pirelli is inconclusive, a few tests at widely differing slacks seeming to show some effect, but whether the differing results obtained are due to slack or other factors has not been determined. The main body of tests, thus far, on 10, 12, and 14-in. motors does not seem to exhibit substantial length dependence. In making up the graph of Figure 2, for example, it was impossible to distinguish between the plotted points representing the several lengths of motors used. In some cases, points for differing lengths of motor lay virtually atop each other.

It would seem safe to say that the inch or so change in motor length which serves builders for altitude control purposes does so in large measure by serving as ballast. On the basis that motor weight approximately equals model weight, then adding 2 in. to a 14-in. motor increases the total flying weight over 7%. Considering that power required increases at an unknown, but far greater than linear, rate with weight the ballasting effect of added motor length in reducing ceiling is easily understandable. None of the test work on motors from 10 through 14 in. in length approaches the above variation.

TEMPERATURE

Rubber powered model aircraft fly better in warm conditions than in the cold. Performance may be improved markedly with an increase in temperature but, despite the common feeling, it is extremely questionable that the improvement is aerodynamic. Since his original cold weather tests on Brown rubber the author has insisted that the improvement in model performance with an increase in temperature is due primarily to an improvement in the torque curve.

A sampling of tests made outdoors in cold weather this past winter reaffirms this contention. Figure 3 shows unwinding torque curves over a variety of temperatures. The lower the temperature, the higher the initial torque but the poorer the torque curve. The higher initial torque is followed by a more abrupt drop in torque as turns are expended. In general those tests made at 18° F exhibited initial torques roughly twice those at 70° F. Matching torques occured after the removal of only 12 to 15% of the total turns, and thereafter cold weather torques became noticeably less.

Variations in the values for specific energy occur in the tests at varying temperatures but these variations are irregular, as the following table shows, and may be due to winding technique or inherent differences in the motors. Insufficient data exist at present to draw any firm conclusion.

SPECIFIC ENERGY
Inch ounces per ounce
0.040 Pirelli
First Wind-Up
120 turns per inch

Motor Length, in.	Temperature °F 70°	18°
14	29400	27000
12	28900	29200
10	31700	31500

The table does not, however, tell the full story. The reader may already have wondered why data at only 120 turns per in. have been given. The answer is that at 120 turns per in. the motors were rock hard at 18° F, half of the test motors breaking on initial wind-ups. On the other hand, motors were far from fully wound at 120 turns per in. under warm weather conditions. At 18° F the highest specific energy on the first wind-up was 31,500 in-oz per oz; at 70° F and 140 turns per in. (still not a "tight" wind) the specific energies ranged from 34,000 to 39,400 in-oz per oz. As the temperature drops the builder is forced to use longer motors to achieve the same turns at torques to which he is accustomed and secures from them poorer performance along with added weight.

Additionally, large flying sites, when heated by the summer sun, frequently have a substantial altitude-dependent temperature differential. At the ceiling the air may be as much as 30 deg. warmer than it is at ground level. It is possible that a climbing model may have the output of its motor improved by the increase in temperature.

There is an interesting but very simple experiment which can be performed to show that temperature changes have a decided effect upon rubber. Tie an end of a 20 to 25-in. length of small Pirelli (0.040 to 0.060-in. will suffice) to one end of a yardstick

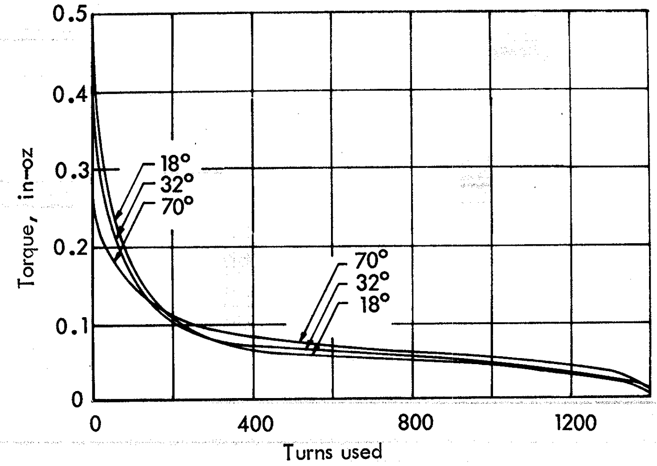

Figure 3. Temperature effects: first wind-up, 12 x .04-in. Pirelli, 120 turns/in.

and to the other end of the Pirelli affix a weight of approximately 2 oz. Note the length of the stretched Pirelli as it supports the weight. Now place this rig where the temperature is well below freezing and note that the length of rubber is greater! Such an experiment we performed had a 23-in. length of Pirelli stretched to 31 in. by a 2-oz load at room temperature. At approximately 20° F the stretched length was 32 in. with the length returning again to 31 in. at room temperature. This provides another area for further investigation. What is the effect of changes in temperature upon the output of an already wound motor?

BACKING OFF TURNS

Over-winding a motor, that is, winding a motor more tightly than is necessary, and then removing some turns, is frequently employed by builders for improving flight performance. A study of the graph of Figure 4 shows clearly why this practice is successful. The graph contains the unwinding torque curves for five motors of identical lengths, third wind-ups (although any series of identical wind-ups shows the same effect), one motor wound to 60 turns per in., one to 80, one to 100, one to 120, and one to 140 turns per in. Compare the residual turns when enough turns have been removed from each motor to drop the torque to 0.10 in-oz. The 140 turn per in. motor still contains 1200 turns while the 60 turn per in. motor contains less than 600. The former still has available twice the turns of the latter, well over twice the energy, and a smooth torque curve. And if we remove turns from both motors at the same rate, when the latter motor is completely unwound the torque of 140 turn per in. motor will have dropped only to the average value of the loosely wound motor -- with still 800 turns left for propulsion.

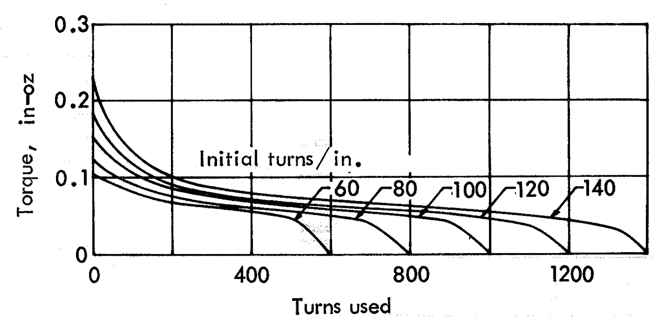

Figure 4. Unwinding torque from various initial torque values: 10 x .04-in. Pirelli, third wind-up, 70° F.

The following table compares values of turns available for three different motor lengths at the reduced torque of 0.10 in-oz .

Motor Length, in.	Turns per inch	Total Turns	Maximum Torque	Turns Remaining at 0.10 in-oz Torque
10	60	600	.10	0
	140	1400	.23	1200
12	60	720	.10	0
	140	1680	.25	1440
14	60	840	.10	0
	140	1960	.26	1700

Backing off turns, however, can be an extremely critical sort of operation, especially near full winds, the extremely rapidly changing torque requiring much care in using the technique.

CONCLUSION

Rubber, despite its apparent vagaries, is a material of rather predictable properties. For example, an almost complete run of tests, at both room and freezing temperatures, had to be discarded because an unfortunate (and avoidable) accident thoroughly mixed some 50 motors. It became impossible to identify motors and to link them to their graph/data sheets and thus to know which motors had two wind-ups, which three, which had been tested at freezing temperatures, which at room temperatures. When this portion of the work, which had to be redone, was redone, the new set of graphs was identical to the originals. Laid one atop the other, the curves for corresponding conditions could not be distinguished, one from the other.

The test facilities would seem entirely suited to the task of rubber evaluation. Torque vs. turns curves can be obtained so easily, to what would seem a most satisfactory degree of accuracy, and in such abundance, to ascertain the effects of any desired variable that the time element has shifted from data taking to data reduction.

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(Refs. 2 through 5 are available from Model Aeronautic Publications, Box 135, Northridge, Calif. 91324, and from NFFS, 1333 So. Franklin St., Denver, Colo. 80210.)