Why might heavier motors fly models higher?

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Summary

The goal of this study was to determine possible causes for the rocket field legend that heavier motors will fly higher when all other factors are equal, and usually in low drag optimized models. The hypothesis was that while the fuel for the motor is tightly controlled during production, motors may weigh different amounts due to differences in how much delay is present. A heavier motor is hypothesized to have a longer delay, causing the model to coast higher, and if the model would otherwise still be going up at ejection, this could provide the supposed performance increase. Motors were massed and then static fired, videoed and analyzed later. The main result is that the variance in delay time was shown to be 80% explained by the variation in initial motor mass. In contrast, the variation in thrust duration of the motors was explained only 2% by variation in the motor masses. These results support the hypothesis and many possible repercussions for the contest and hobby rocket modeler are discussed. Lighter motors have significantly shorter delays and could be used when a short delay motor is not available for an appropriate model like a rocket glider. Heavier motors have significantly longer delays and could (continue) to be used in minimum diameter optimized altitude or streamer models for instance. These differences could be taken into account for rocket trajectory simulations and could have a positive impact on the contest rocketry community. Further testing could include: static test stand data instead of just video, x-rays of motors to determine length of the thrust and delay sections, and actual flight testing.

ORIGINAL

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Objectives and Hypothesis

A common rocket field legend is that motors with higher mass within the same motor type will yield better performance. This report investigates possible causes of this phenomenon using simple techniques and common equipment. The hypothesis is that the mass differences are not necessarily caused by additional propellant, but are caused by additional delay, benefiting high performance models that are still going up when a normal delay would fire the ejection charge.

Background

Several reports have massed motors, but none known have attempted to correlate this mass with performance or additional delay, however all known relevant data is reviewed.

First, some background on motor production. This report is concerned only with black powder motors, produced mainly by Estes. Typical data sheets provided by NAR Standards and Testing include data on the dimensions of the casing and a typical thrust curve. Mean and standard deviations of total impulse, peak thrust, and burn time are provided. Little data on the delay lengths or variations is included, just the published delay time and mean measured delay [1, 2].

An employee of Estes Industries recently provided interesting information with regards to the manufacturing of their black powder motors. Each batch of black powder made has different properties, due to the materials used, and each batch burns at a different rate. Each batch of black powder must be tested and motors made will have varying masses of black powder so that each motor ends up with the appropriate total thrust for the engine type [3]. No information was given on the makeup of the delay train.

A report conducted for the purposes of practicing for the Random Duration event indicated a significant correlation between motor age and performance [4]. The relevant conclusion was that older motors had a lower performance, though the motors had not been massed so it is hard to draw direct analogies to this work.

A report testing performance of helicopter designs in flight and varying the dihedral massed 48 1/2A3-2T motors, 44 motors were in the 5.9-6.1 gram range, 4 motors outside this range [5]. Though it is not mentioned whether these motors were from the same batch or date code, the distribution of motor masses is similar to the findings here.

A previous report showed that the delay times of Estes (and the now out of production Apogee black powder motors) often fell outside of the allowable range as dictated by the NFPA and NAR Standards and Testing [6]. Many different types of motors were tested (A8-3, B4-4, etc) but no correlation with motor mass was done. In this report, delay time was measured by a stopwatch after motor burnout done with static (ground) testing.

The primary testing of motors was constructed on Apogee sold and Estes produced 1/4A3-4T motors, purchased from Ed LaCroix after they lost contest certification, but were still safety certified. These motors were made in bulk by Estes and sold to Apogee who then labeled and sold them at retail, and were identical in construction to the 1/4A3-4T motors Estes previously sold. As they were made in a single batch, all had the same date code and represented 24 like motors, the best set available for testing the hypotheses of this report [7].

For international competition, finding composite motors without voids and with proper delay times proved critical to the success in glider and altitude events. For these reasons, many motors were x-rayed for these purposes. In the motors for glider events, finding motors without voids was critical, as voids could produce slightly higher bumps in thrust, resulting in a shred as the model would go faster than the wing could handle. For the altitude event, having very accurate knowledge of the length of the delay train in the composite motors also proved critical to success [8]. Very little work with black powder motors was done, though the results could be extended. Access to x-ray equipment would be a great addition to this report, unfortunately no such access could be obtained within the budget and time limitations of this report.

The author has entered two previous Research and Development reports, both concerned with drop testing of recovery systems. The first concerned the most appropriate facilities for testing various recovery methods [9], the second used the knowledge gained from the first to test shroud line length affect on parachute descent rate, finding 75 cm shroud lines being optimal for 50 cm parachutes [10]. Neither of these reports have any relevance to this work.

In summary, though knowledge of the differences in mass of motors and knowledge of the length of delay train affecting performance existed, in no previous work have these two facts been examined in the same motor.

Methods and Materials

Two primary tests were conducted. First, several Estes (or Apogee sold Estes produced) motors were massed with an electronic scale accurate to 0.1 grams. The date code of each motor was recorded along with the mass. Some of these motors were to be tested using the second main test, others were simply massed to obtain further estimates of the distributions within and between different date code batches.

The second main test was to test fire motors. In lieu of a real test stand, each motor was filmed using a Nikon Coolpix S1 in video mode. These could be later analyzed to determine the duration of motor thrust, the duration of delay and ejection charge timing. This is in contrast to the approach taken by another report, which timed each motor as they were static fired [6]. Having video comprising the full flight from ignition to ejection allows the timing to be as accurate as the video capture speed, instead of being affected by the timer. These motors were test fired in the author's parents' backyard, taped to a launch rod and fired 'up' and using bare nichrome igniters so the initial puff seen on video was definitely the motor ignited not the pyrogen on the igniter tip. After the first video test, the camera was optically zoomed in to capture as much detail of the motor launch sequence as possible.

Other tests performed, though not as heavily relied upon in the analysis were to carefully disassemble the motor in a controlled environment and measure the length of the thrust producing portion of the motor and the delay train. This test was difficult due to the lengths varying little and accurate calipers not being handy. Also during disassembly the motor pieces would crumble, making accurate measurements very difficult. Access to an x-ray machine would be highly preferred for this step, especially since motors disassembled could not be test fired, so no actual correlation in length and duration of delay could be made.

Results were analyzed using Pearson Correlation Coefficient, to determine the correlation between motor mass and delay time or thrust time.

The budget for the project included mostly motors and igniters as disposable, plus some standard rocketry items to ignite the motors, an on-hand digital video camera of low quality and an old tripod used to mount it. Many other motors were used as what was on-hand in my range box but were only massed not test fired.

The items used are summarized below as well as their cost, roughly 280$ of equipment on hand was used in total and 36.45$ of motors and igniters were purchased and consumed in testing.

Fliskits undipped Q2 igniters (30 for 12.45$)
24 apogee 1/4A3-4T motors (24 for 24$)
Cen-tech 93543 Electronic Scale (10$ from Harbor Freight)
Launch Controller from Estes Star Wars Naboo Fighter starter kit purchased on clearance (10$)
Nikon Coolpix S1 Camera (150$)
Old tripod (10$ yard sale)
Other motors, Estes, various types, not destroyed (estimated 100$)

Results

First, shown in Table 1 is the distribution among several various packs, grouped by date code, of masses of A3-4T motors.

Table 1			A3-4T		
mass (grams)	a050301	a090808	a012808	a022802	a013100
7.8	2				
7.9	2			1	
8	2		1		1
8.1	1	1			
8.2		1		1	
8.3		1	1		
8.4			2		

Shown in Table 2 is the count of motors of each mass of the batch of 24 Apogee sold Estes manufactured 1/4A3-4T motors. The masses are around the range reported on the NAR S&T fact sheet [1].

Table 2 count	Apogee 1/4A3-4T mass (grams)
2	5.3
4	5.6
7	5.7
9	5.8
1	5.9
1	6.2

13 of the 24 motors in this batch were test fired according to the procedure described. All of the outliers and several from the 5.6, 5.7, and 5.8 gram batches. The motors were massed again to determine expelled mass post firing. No attempt was made to clean residue from the motor casing. The video was analyzed frame-by-frame to determine start of thrust, end of thrust, and ejection. Results of these tests are reported in Table 3.

Table 3 1/4A3-4T Static Firing Tests

before mass (g)	after mass (g)	expelled mass (g)	thrust time (s)	delay time (s)	thrust plus delay (s)
5.3	3.4	1.9	0.33	1.37	1.7
5.3	3.4	1.9	0.4	1.4	1.8
5.6	3.4	2.2	0.46	2.85	3.31
5.6	3.5	2.1	0.33	3.03	3.36
5.7	3.4	2.3	0.51	2.82	3.33
5.7	3.5	2.2	0.52	2.94	3.46
5.7	3.7	2.0	0.55	3.02	3.57
5.8	3.6	2.2	0.38	3.09	3.47
5.8	3.5	2.3	0.35	2.84	3.19
5.8	3.6	2.2	0.39	3.3	3.69
5.8	3.6	2.2	0.43	3.18	3.61
5.9	3.6	2.3	0.45	3.2	3.65
6.2	3.6	2.6	0.4	3.88	4.28

Of concern was the accuracy of determining the end of the thrust phase and beginning of delay. For this reason the raw video was analyzed again and the time to peak thrust was determined. As the thrust profile for this motor is an inverted ‘V’ shape, the thrust peak should be halfway through the motor thrust phase [2]. By measuring the time from start (easily detectable) to peak (longest flame from motor) and doubling it to calculate the thrust duration, Table 4 was constructed.

Table 4 1/4A3-4T Static Firing Tests (Peak Thrust Time Method)

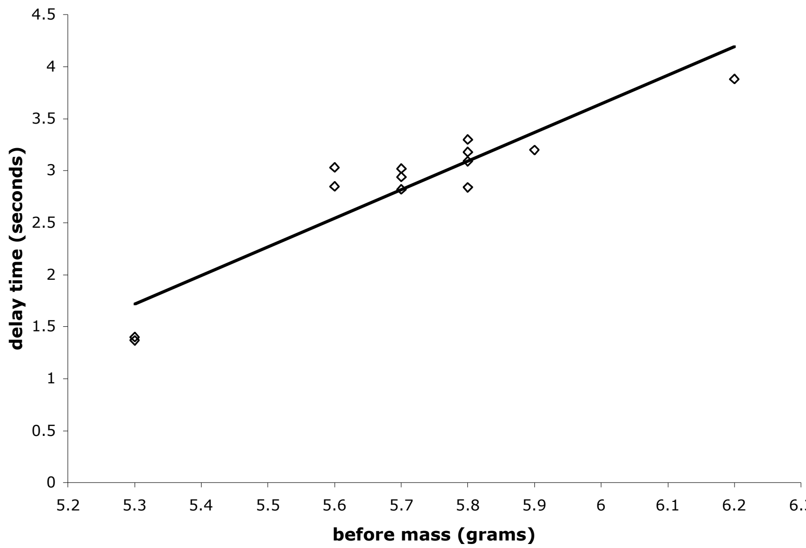
before mass (g)	after mass (g)	expelled mass (g)	thrust time (s)	delay time (s)	thrust plus delay (s)
5.3	3.4	1.9	0.58	1.12	1.7
5.3	3.4	1.9	0.58	1.22	1.8
5.6	3.4	2.2	0.5	2.81	3.31
5.6	3.5	2.1	0.4	2.96	3.36
5.7	3.4	2.3	0.44	2.89	3.33
5.7	3.5	2.2	0.38	3.08	3.46
5.7	3.7	2	0.66	2.91	3.57
5.8	3.6	2.2	0.58	2.89	3.47
5.8	3.5	2.3	0.44	2.75	3.19
5.8	3.6	2.2	0.54	3.15	3.69
5.8	3.6	2.2	0.54	3.07	3.61
5.9	3.6	2.3	0.62	3.03	3.65
6.2	3.6	2.6	0.54	3.74	4.28

The mean and standard deviation of the thrust duration in Table 3 is 0.4231 and 0.0718. In table 4 they are 0.5231 and 0.0860. The mean and standard deviation of the delay time according to the first method shown in Table 3 are 2.84 and 0.702. For Table 4 they are 2.74 and 0.738.

To examine the correlation between the before mass and the other measurements taken, both correlation coefficients and Pearson correlation coefficients were computed to determine how much of the variance in the other measurement can be explained by the variation in the initial mass. These are shown in Table 5.

Table 5	after mass (g)	expelled mass (g)	thrust time (s)	delay time (s)	thrust plus delay (s)	thrust time, peak method (s)	delay time, peak method (s)
Pearson Correlation Coefficient (before mass)	0.65	0.91	0.16	0.93	0.91	-0.01	0.90
Correlation Coefficient (before mass)	0.65	0.91	0.16	0.93	0.91	-0.01	0.90
$(\text{Correlation Coefficient})^2$	0.43	0.83	0.02	0.86	0.84	0.00	0.80
p-value (2-tailed)	0.161	0.000016	0.601	0.000004	0.000016	0.974	0.000028

The before mass and delay time calculated are shown in Chart 1 with a linear fit trendline.



Attempts to measure the 11 remaining motors from this batch of 24 by disassembling them and measuring the various components (thrust, delay, ejection) did not yield useful data.

Discussion

The results, with the caveats due to the relatively simple experimental techniques used, are striking and agree with the hypothesis. First, according to the massing experiments on A3-4T motors it seems there is some variation between batches and within batches as to initial motor mass. Within the single batch of 24 1/4A3-4T motors there is a range of motor mass varation, it would be safe to call the distribution Gaussian. There are many motors with a medium mass and just a few with a very low or very high mass.

The variation in thrust time is not explained by the variation in motor mass very well, if at all, though the difficulties in determining the motor thrust time and the relatively short duration could be contributing factors here. Regardless of the method of determining the duration of the thrust the duration of the delay is well correlated with the initial motor mass. At the worst estimate, 80% of the variance in thrust time can be attributed to the variance in initial motor mass.

If these results are correct and hold true for all Estes-type black powder motors, there are important applications. In contest rocketry, many types of models would benefit from an additional delay, particularly where the Estes type motors are only available in a medium length delay, for instance the A3-4T or B4-4, whereas most contest altitude or streamer duration models could use a currently out of production and contest decertified A3-6T or B4-6, particularly when a piston is employed.

These results also explain the rocket field legend that heavier motors will lead to higher altitudes. It could be that these heavier motors have more propellant or burn longer or go higher, or have a very different thrust pattern, all of these were not tested due to the lack of a test stand, but some of them have been ruled out, at least in testing this batch of motors.

Also, these results support and could explain earlier results on delay variation [6], as most of the delays measured here would be outside the allowed range for a 4 second delay motor, indeed none of these motors actually had a 4 or more second delay.

Also of note is the lower mass motors. Again, for some motor types and contest models the delay may be too short, for instance many rocket gliders need an A3-2T not a A3-4T or even A10-3T, however the A3-2T is not available currently. Massing motors may prove advantageous for these model types as well.

Also, given the current lack of delay choices in some motor classes, selecting longer or shorter mass motors could prove advantageous for sport flying as well. The perfect ejection and apogee could be dialed in if more experiments conclude that the source of the variance in delay time is the motor mass, and with enough data it could be possibly to achieve ejection at apogee more frequently.

The last point of interest is that if these results are true, contest modelers will need to buy a large amount of motors to find the few very heavy or very light motors. Perhaps they will resort to hunting through motors with a scale much like current modelers buy the lightest balsa they can find.

Conclusions and Future Work

In conclusion, for this class of now contest decertified motors it appears that caveats withstanding, the variation in delay timing can be explained well by initial motor mass variation. If a properly designed contest or other model can still be going up when a normal delay would fire the ejection charge, using a heavier motor could allow the model to coast further to apogee, which explains the rocket field legend that heavier motors will go higher.

Of course, these experiments were relatively simple. An ideal experiment would be to test all types of black powder motors in large batches. Motors could be massed as in this report and x-rayed as others have done[8] to determine if the mass differences correlate to longer delay trains in the motor. Also, use of a static test stand to fire these motors would lead to better data as it could establish whether the thrust phase actually produced more thrust, not just if it is was longer or shorter. Finally, the real test would be to fly models with various mass motors and track them to see if the heavier models do indeed fly higher. All these tests are suggested for future work.

References

1. ***Estes A3T. 1996, NAR Standards and Testing.***

2. ***Estes 1/4A3T. 1998, NAR Standards and Testing.***

3. ***Dorffler, M. Ye Olde Rocket Forum. [Forum Posting] 2009 [cited July 24, 2009]; http://forums.rocketshoppe.com.***

4. ***Giugliano, E., Using a Designed Experiment to Determine Flight Duration of a Model Rocket or "Taking the 'random' out of random duration". 1999.***

5. ***Miller, A., Studying the effects of various dihedrals on 1/2A helicopters. NAR Technical Review, 1992. 10(NARAM 34): p. 6.***

6. ***Ring, C., Reliability of Deployment Systems of Black Powder Motors. NARAM-41, 1999.***

7. ***LaCroix, E., Personal Communication with R.G. Coleman. 2009.***

8. ***Kreutz, B., Personal Communication with R.G. Coleman. 2009.***

9. ***Coleman, R.G., Limiting Factors in Drop Testing Recovery Systems, in NARAM 40. 1998: Muncie, Indiana.***

10. ***Coleman, R.G., Optimum Shroud Line Length for 50 cm Parachutes, in NARAM 41. 1999: Pittsburgh, Pennsylvania.***