

Effects of Boat Tail Taper Angle on Model Rocket Drag During Free Flight

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Abstract

Boat tails are tapered rear extensions that reduce base drag in vehicles, but their effectiveness depends on taper angle. Previous computational and wind tunnel studies predict an optimal subsonic boat tail angle near 14-16°. This study evaluated 0°, 7°, 14°, and 21° boat tails on an Estes Big Bertha model rocket. We hypothesized that the 14° boat tail would produce the lowest drag coefficient consistent with predictions of an optimum near 14-16°. Flight acceleration was recorded with a Vernier Go Direct Accelerometer, and velocity was determined by integrating acceleration over time. Drag coefficient was calculated during the unpowered coast phase after motor burnout, between 15 and 28 m/s. The mean experimental drag coefficients were 0.663 ± 0.016 , 0.673 ± 0.016 , 0.406 ± 0.016 , and 0.572 ± 0.016 for the 0°, 7°, 14°, and 21° configurations respectively. The 14° boat tail produced the lowest drag, with a 38.7% reduction in drag coefficient relative to the 0° baseline. OpenRocket simulations based on launch site atmospheric conditions were compared with the experimental results. OpenRocket predicted smaller reductions, with mean drag coefficients of 0.604, 0.569, 0.572, and 0.589. The 7° and 14° boat tails had similar simulated drag. The experimental performance of the 14° boat tail is consistent with previous research describing airflow separation and reattachment near this taper angle. These results indicate the potential of low-cost model rocket flight tests for analyzing aerodynamic predictions under real flight conditions.

Keywords: aerodynamics, boat tail, drag coefficient, OpenRocket, free flight.

Introduction

Aerodynamic efficiency directly dictates a vehicle's ability to move through a fluid, impacting speed, range, and fuel consumption (1). In the real world, it directs the payload capacity of rockets and their fuel efficiency, reducing the cost of launching into orbit. In projectile vehicles such as model rockets, minimizing aerodynamic resistance is critical for improving performance, particularly during the unpowered "coast" phase following motor burnout (2). In high-velocity, axisymmetric bodies such as rockets, base drag significantly influences overall drag (3, 4). This drag occurs because flow separation on the rear of bodies creates a low-pressure zone, producing a backward aerodynamic force (1, 3, 5). Boat tails are tapered base extensions that mitigate this effect by delaying flow separation along the body length and reducing the size of the low-pressure zone (3, 4). However, the effectiveness of a boat tail is directly correlated to its geometry, particularly the taper angle (3, 4, 6).

Previous research has shown that the optimal boat tail angle lies between 14-16° in subsonic regimes (3, 4). This is because at taper angles between 12-18°, a "separation bubble" forms near the boat tail, allowing the flow to eventually reattach around the backside of the bubble (3). This reattachment results in the most effective drag reduction as it minimizes the low-pressure zone volume while ensuring the flow does not fully separate. This research has also shown that an optimal boat tail, at subsonic speeds, can reduce the drag coefficient of a body by up to 55%, with the most significant reductions observed in a simulated subsonic flight regime, where base drag is the strongest force (3, 4). Furthermore, when additional drag reduction techniques such as base bleed (ejecting hot gas from the base of a projectile) and

base cavity (an indentation at the base of a projectile) are applied, the drag coefficient of an axisymmetric body can be decreased by up to 60% when combined with a boat tail (4). Rear tapering also produced drag reductions in non-axisymmetric bodies and heavy-vehicle configurations (6, 7, 8, 9). These studies demonstrate that rear tapering can reduce drag across substantially different vehicle geometries.

Existing research has primarily studied boat tail aerodynamics using computational fluid dynamics and wind tunnel testing (3, 4, 6, 10). Experimental low speed testing by Tran et al. further compared 10°, 14°, and 20° axisymmetric boat tails at a Reynolds number of approximately 4.3×10^4 . The 10° configuration maintained attached flow, while separation bubbles were observed for the 14° and 20° configurations. Of these three boat tail geometries, the 14° boat tail produced the lowest pressure drag (11). Separate research has also shown methods for reconstructing aerodynamic drag from model rocket flight data (2). However, fewer studies have directly compared multiple boat tail taper angles using free flight measurements from similar small rockets. Free flight introduces factors such as wind, launch trajectory, and vehicle orientation that are difficult to reproduce in controlled simulations or wind tunnel experiments (2, 10, 12). Therefore, this study aims to experimentally characterize the relationship between boat tails with varying taper angles and drag coefficient of a model rocket in subsonic regimes. We hypothesized that the 14° boat tail would produce the lowest drag coefficient, and found a 38.7% reduction in mean drag coefficient compared to the 0° baseline, consistent with the previously predicted optimum near 14-16°.

Methodology

To determine the optimal drag reduction predicted by existing literature, four boat tails were designed, with taper angles of 0°, 7°, 14°, and 21°. These taper angles were selected to bracket the theoretical optimal boat tail angle of 14-16° identified in literature (3, 4). The range allowed for drag across 3 flow regimes to be observed: attached flow (0-7°), the separation bubble transition (14°), and fully separated flow (21°) (3).

The boat tails were designed using Autodesk Fusion 360 and fabricated on a Bambu Lab X1 Carbon 3D printer (Figure 1). All four boat tails were printed using Overture white ABS filament with a layer height of 0.2 mm. To minimize the differences in total rocket mass between boat tail configurations, the infill density was adjusted for each configuration: the 0°, 7°, 14°, and 21° boat tails were printed with 10%, 12%, 15%, and 21% infill respectively. The resulting masses were 12.0 g, 11.6 g, 11.3 g, and 11.0 g.

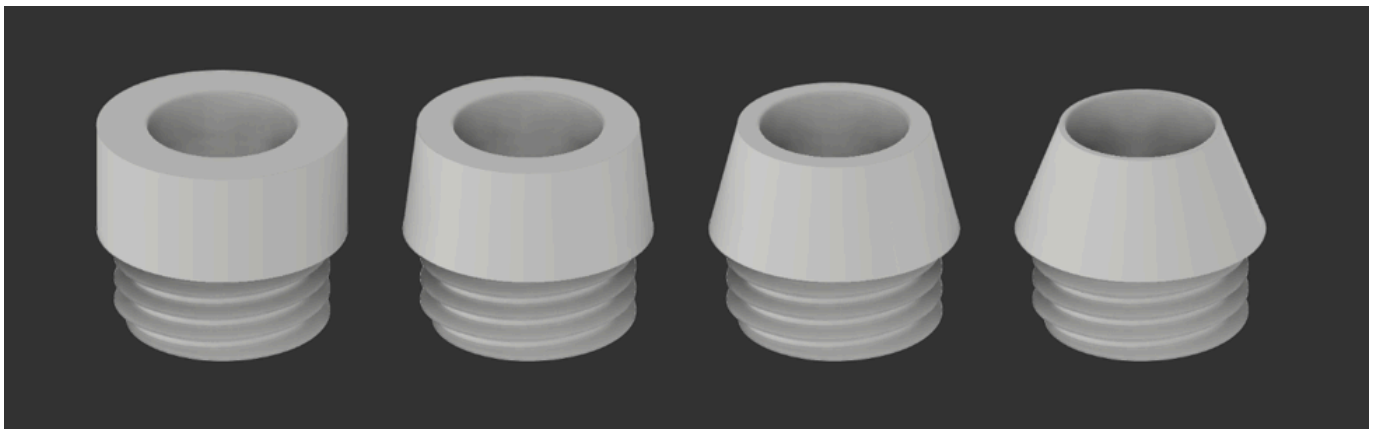


Figure 1. Rendering of the boat tails used in the experiment. CAD models of the 0° , 7° , 14° , and 21° boat tails are shown from left to right at the same scale. All boat tails had a length of 35 mm and a maximum diameter of 41.6 mm. The end of each boat tail, opposite of the modeled threads, had diameters of 41.60, 36.93, 32.13, and 27.01 mm for the 0° , 7° , 14° , and 21° boat tails respectively.

The experimental vehicle was an Estes Rockets Big Bertha Model Rocket kit with an external diameter of 41.6mm and length of 62cm. The rocket was constructed from a brown kraft paper body tube, balsa wood fins, and a polystyrene nose cone. The model rocket's propulsion was provided by an Estes Rockets C6-5 Model Rocket Engine, ensuring the rocket remained within a subsonic regime. Flight data was recorded using a Vernier Go Direct Acceleration Sensor at a sampling rate of 500 Hz. The completed vehicle and major components are shown in Figure 2.

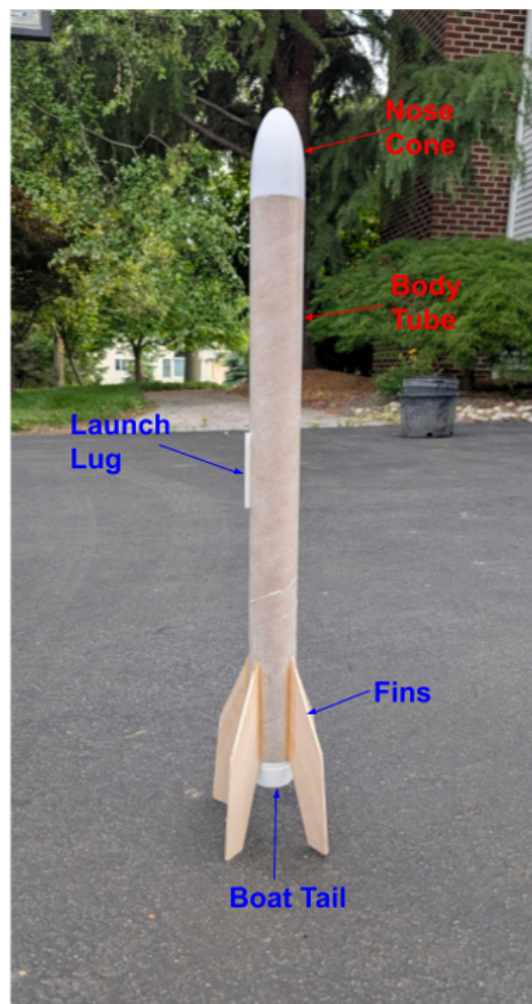


Figure 2. Experimental model rocket configuration. Photograph of the completed Estes Big Bertha model rocket with a boat tail installed. The nose cone, body tube, launch lug, fins, and boat tail are labeled.

To determine accelerometer measurement uncertainty, the sensor was tested while stationary in the same orientation used in flight. Three ten second trials were recorded at 500 Hz. The mean stationary acceleration was -9.8206 m/s^2 , compared to the expected value of -9.81 m/s^2 . This measured bias was incorporated into the gravity correction applied to the flight data. The average standard deviation of the three trials was 0.0352 m/s^2 , which was used as the random acceleration measurement uncertainty. Because velocity was calculated by trapezoidal integration of acceleration, acceleration uncertainty was propagated into velocity at each time step. For independent random acceleration errors, we used the equation:

$$\sigma_{v,n}^2 = \sum_{i=0}^n (w_i \Delta t)^2 \sigma_a^2 + (t_n \sigma_b)^2$$

where v, n is the uncertainty in the integrated velocity at the n th sample, n is the sample we calculated uncertainty at, w_i is the trapezoidal integration weight, t equals the 500 Hz sampling interval of 0.002s, a equals the random acceleration uncertainty, 0.035194 m/s^2 , measured from the stationary launch tests, and b equals the estimated acceleration bias correction, 0.001298 m/s^2 .

Measurement uncertainty in drag coefficient was propagated from rocket mass (m), acceleration (a), atmospheric pressure (P), temperature (T), velocity (v), and body diameter (d) using root-sum-square propagation:

$$\frac{\sigma_{Cd}}{|Cd|} = \sqrt{\left(\frac{\sigma_m}{m}\right)^2 + \left(\frac{\sigma_a}{a}\right)^2 + \left(\frac{\sigma_P}{P}\right)^2 + \left(\frac{\sigma_T}{T}\right)^2 + \left(2\frac{\sigma_v}{v}\right)^2 + \left(2\frac{\sigma_d}{d}\right)^2}$$

where m , measured using a scale, equaled 0.1531, 0.1528, 0.1524, and 0.1521kg for each rocket configuration using the 0° , 7° , 14° , and 21° boat tails respectively, and m equaled 0.00005kg. Additionally, P , obtained from converting the altimeter setting from the nearby Trenton-Mercer Airport Automated Surface Observing System (TTN ASOS) to station pressure using the NWS station pressure conversion and station elevation, equaled 101584 Pa. Similarly, T was obtained from the TTN ASOS, 296.45 K. Published ASOS temperature RMSE and pressure sensor accuracy were used as the respective measurement uncertainties: 0.50 K and 67.2 Pa. Finally, d was measured using a set of calipers, 0.0416m, with d equaling 0.00005m. The propagated uncertainty was calculated at each time step within the 15 - 28 m/s analysis interval, and the mean uncertainty was calculated for each boat tail configuration.

Each boat tail was mounted using modeled screw threads that engaged with an adapter epoxied into the aft end of the rocket body. The boat tails were installed flush with the body tube to maintain a smooth transition between the body tube and the boat tail.

Aerodynamic performance was quantified using the drag coefficient (C_d), derived from the deceleration of the model rocket during the unpowered coast phase (2). Because thrust was 0 during this period, the accelerometer data directly represented the deceleration caused by aerodynamic drag (F_D). Therefore, the drag force was calculated using Newton's Second Law:

$$F_D = ma$$

where m = rocket mass and a = rocket acceleration. Velocity (v) was determined by integrating the total acceleration over the time from launch to apogee. With drag force and velocity known, the drag coefficient was computed by using the equation:

$$C_d = \frac{2F_d}{\rho v^2 A}$$

where ρ represents the local air density and A is the rocket's cross-sectional area: 0.001359m^2 . The local air density was calculated using the Ideal Gas Law:

$$\rho = \frac{P}{RT}$$

where P = absolute pressure in Pascals (Pa), R = gas constant for dry air ($287.05\text{ J}/(\text{kgK})$) and T = temperature in Kelvin (K).

To model and simulate the test vehicle in OpenRocket, the manufacturer's RockSim file of the Estes Big Bertha was imported as a baseline model (13). The custom modifications were then recreated to represent the physical rocket. To account for the internal boat tail adapter, an inner tube was added with the adapter's dimensions and measured mass (4.7 grams), ensuring accurate mass distribution (13, 14). To model the boat tails, an external transition was added using the external length, fore diameter, and aft diameter dimensions from the Fusion 360 CAD models. The mass of the transitions was overridden for the 0° , 7° , 14° , and 21° boat tails to match their physical weights of 12g, 11.6g, 11.3g, and 11g respectively. Before simulating the flight, the recorded launch day atmospheric and weather conditions (1.194 kg/m^3) were input into the simulation settings to ensure air density matched real-world conditions (Table 1). Finally, to match the accelerometer's sampling rate, the simulation's time step was set to 0.002 seconds, and the resulting time (s), altitude (m), total velocity (m/s), total acceleration (m/s^2), and drag force (N) were exported in CSV format.

Table 1. OpenRocket simulation parameters used for all boat tail configurations.

Latitude	40.33 °N
Longitude	74.59 °W
Launch site altitude	65 m
Temperature	23.3 °C
Atmospheric pressure	101584 Pa
Wind speed	0 m/s
Motor	Estes C6-5
Launch rod length	0.914 m

Launch rod angle	0°
Minimum simulation time step	0.002 s
Aerodynamic calculation method	Extended Barrowman
Simulation method	6-DOF Runge-Kutta 4

Results

To compare the aerodynamic performance of each boat tail, the unpowered coast phase was analyzed, specifically between velocities of 15 and 28 m/s. The 0° baseline configuration had a mean drag coefficient of 0.663 ± 0.016 . The 7°, 14°, and 21° configurations had mean drag coefficients of 0.673 ± 0.016 , 0.406 ± 0.016 , and 0.572 ± 0.016 respectively (Table 2). The 14° boat tail produced the lowest mean drag coefficient, corresponding to a 38.7% reduction compared to the 0° baseline. The 21° boat tail reduced mean drag coefficient by 13.7%, while the 7° boat tail produced a 1.6% increase relative to the baseline.

Table 2. Experimental effect of boat tail taper angle on drag coefficient. Mean drag coefficient was calculated from all time samples within the 15 - 28 m/s unpowered coast phase interval. Percent change is relative to the 0° baseline configuration. One flight was performed per configuration. “# of Samples” refers to 500 Hz time samples.

Taper Angle	Mean Drag Coefficient	Mean propagated uncertainty	Percent Change From 0°	# of Samples
0°	0.663	0.016	0%	568
7°	0.673	0.016	+1.6%	567
14°	0.406	0.016	-38.7%	599
21°	0.572	0.016	-13.7%	579

The effect of boat tail geometry is shown in Figures 3 and 4. After each rocket decelerated to 28 m/s, the 14° configuration decelerated less rapidly relative to the other configurations. Accordingly, its velocity decreased more slowly, resulting in the longest time to decelerate from 28 to 15 m/s. The 0° and 7° configurations had similar accelerations and velocities, while the 21° configuration generally lay between the 14° and baseline configurations.

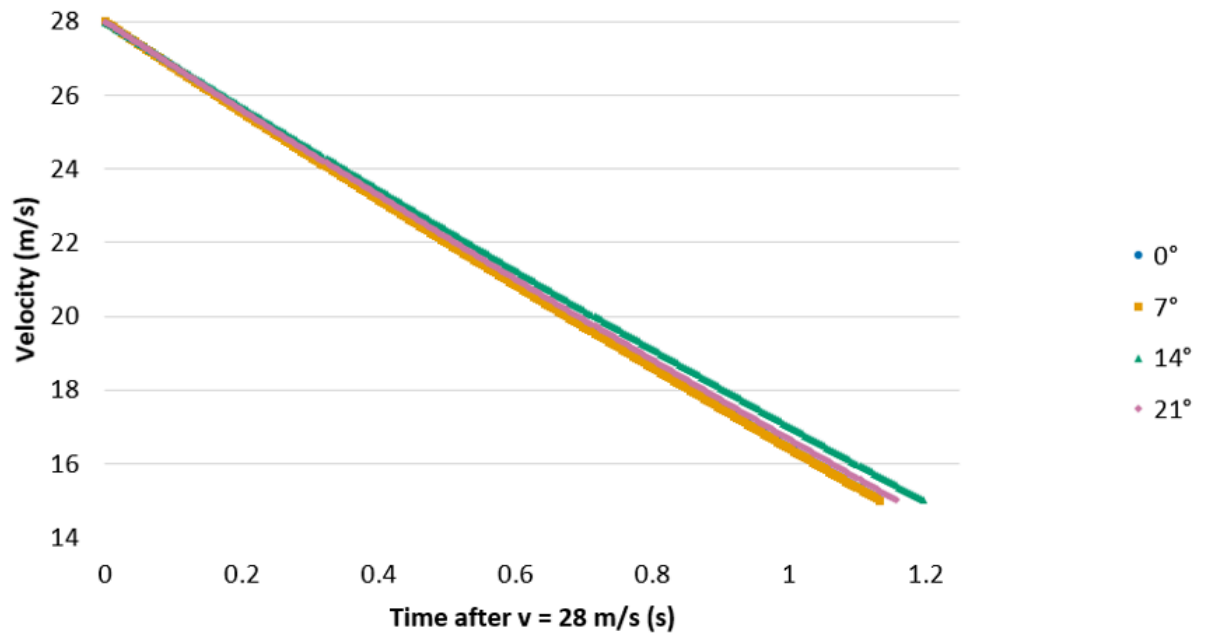


Figure 3. Experimental coast phase flight dynamics for each boat tail configuration. Velocity as a function of time after each rocket decelerated to 28 m/s. Data is shown until each rocket decelerated to 15 m/s.

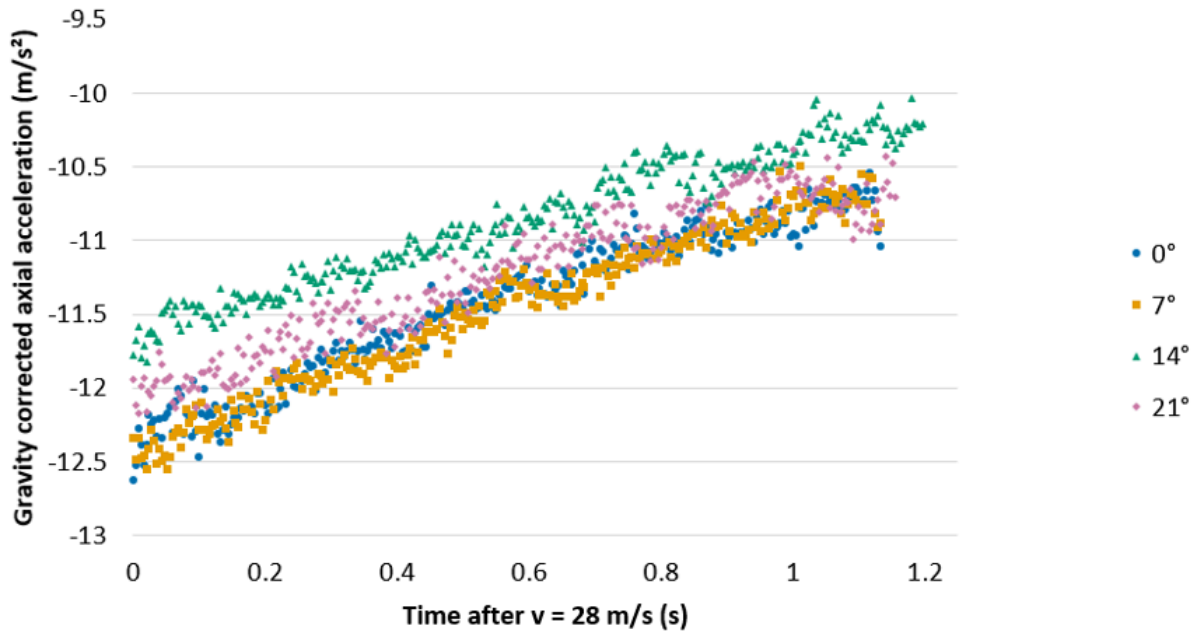


Figure 4. Experimental coast phase flight dynamics for each boat tail configuration. Gravity corrected axial acceleration as a function of time after each rocket decelerated to 28 m/s. Data is shown until each rocket decelerated to 15 m/s.

Drag coefficient also varied throughout the coast phase (Figure 5). The 14° boat tail generally maintained the lowest calculated drag coefficient across the entire 15 - 28 m/s interval. The 0° and 7° configurations remained similar, while the 21° configuration generally produced drag coefficients between that of the 14° and baseline configurations. Because drag coefficient varied with velocity, the same 15 - 28 m/s interval was used for all configurations to maintain a consistent comparison range. The standard deviations of drag coefficient were 0.052, 0.045, 0.059, and 0.073 for the 0°, 7°, 14°, and 21° configurations respectively. These values describe the variation of the calculated drag coefficient during each flight, rather than the measurement uncertainty of drag coefficient.

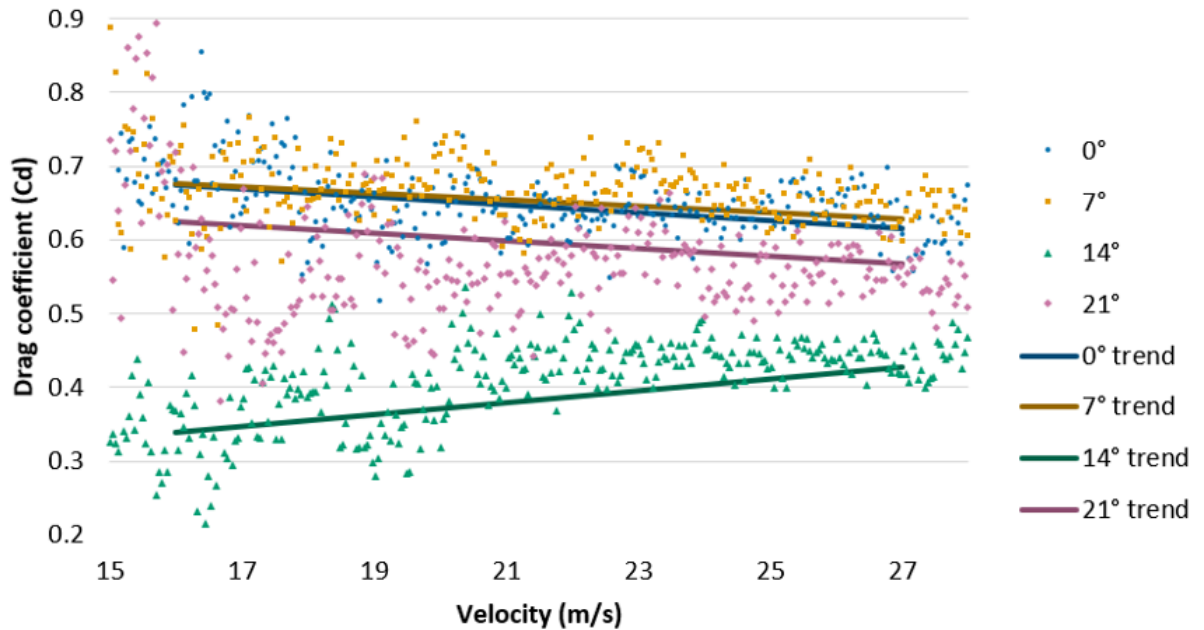


Figure 5. Experimental drag coefficient as a function of velocity. Drag coefficient was calculated throughout the 15 - 28 m/s unpowered coast phase interval for the 0°, 7°, 14°, and 21° boat tail configurations. The 14° configuration generally maintained the lowest calculated drag coefficient throughout the analyzed interval. Each trendline runs from 16 - 27 m/s, with each endpoint using an 11 point centered average.

OpenRocket simulations were also analyzed across the same unpowered coast phase velocity range of 15 - 28 m/s (Figure 6). The 0° baseline configuration produced a mean simulated drag coefficient of 0.604. The 7°, 14°, and 21° configurations produced mean simulated drag coefficients of 0.569, 0.572, and 0.589 respectively (Table 3). Relative to the 0° baseline, this corresponds to a reduction in simulated drag coefficient of 5.7% for the 7° boat tail, 5.3% for the 14° boat tail, and 2.4% for the 21° boat tail. The 7° and 14° configurations produced highly similar simulated drag coefficients, with a difference of approximately 0.0024, while the 21° configuration showed a smaller reduction from the baseline.

Table 3. OpenRocket-predicted effect of boat tail taper angle on drag coefficient. Mean simulated drag coefficient was calculated from the 15 - 28 m/s unpowered coast phase interval for each configuration. Simulations used identical launch conditions, and percent change is relative to the simulated 0° baseline.

Taper Angle	Simulated Mean Drag Coefficient	Percent Change From 0°
0°	0.604	0%
7°	0.569	-5.7%
14°	0.572	-5.3%
21°	0.589	-2.4%

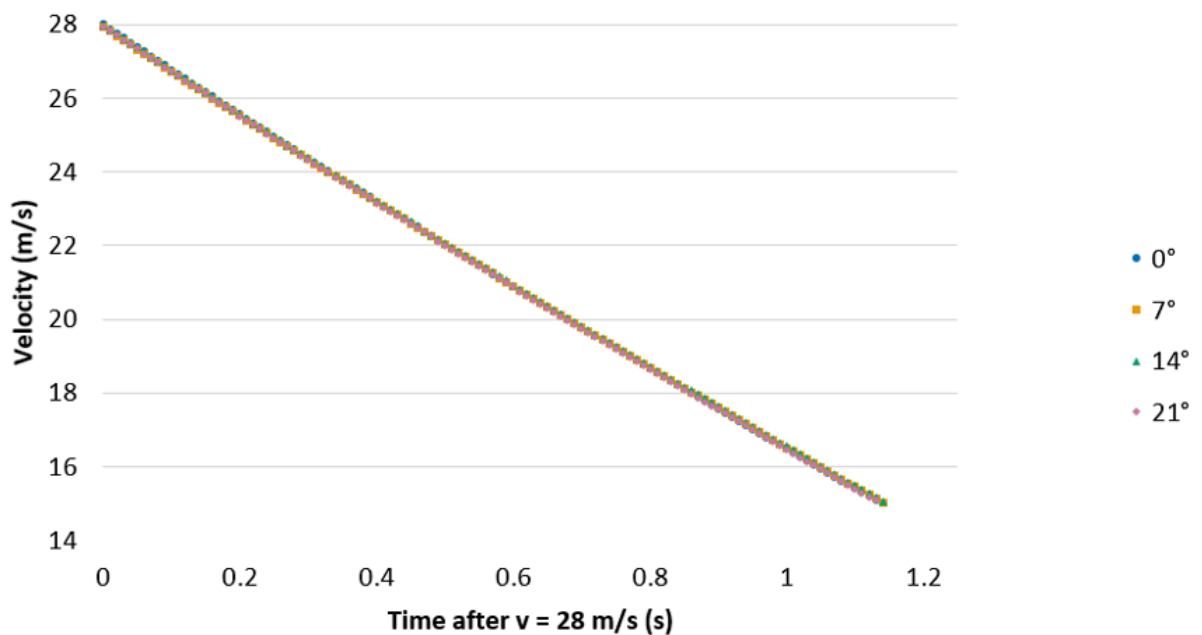


Figure 6. OpenRocket simulated coast phase flight dynamics for each boat tail configuration. Velocity as a function of time after each simulated rocket decelerated to 28 m/s. Data is shown until each simulated rocket decelerated to 15 m/s.

Discussion

The experimental results reveal that the 14° boat tail produced the greatest drag reduction of the four boat tail configurations tested. Across the analyzed coast phase velocity range of 15 to 28 m/s, the 0°, 7°, 14°, and 21° boat tails produced mean drag coefficients of 0.663 ± 0.016 , 0.673 ± 0.016 , 0.406 ± 0.016 , and 0.572 ± 0.016 respectively. The 14° boat tail therefore reduced the mean drag coefficient by approximately 38.7% compared to the 0° baseline. This result is consistent with previous CFD and wind tunnel research identifying an optimal boat tail taper angle near 14-16° in subsonic flow (3, 4, 11).

However, the OpenRocket simulations predicted a much smaller effect from changing the boat tails. OpenRocket's simulated mean drag coefficients were 0.604, 0.569, 0.572, and 0.589 for the 0°, 7°, 14°, and 21° configurations respectively. While all 3 tapered configurations reduced simulated drag compared to the baseline, OpenRocket predicted the 7° and 14° configurations to perform almost identically, with drag coefficient reductions of approximately 5.7% and 5.3% relative to the baseline. Therefore, the experimental and simulated data both showed an improvement for the 14° configuration compared to the 0° baseline but did not predict similar magnitudes of drag reduction or the same optimal taper angle. This difference may result from limitations in OpenRocket's aerodynamic simulation model. OpenRocket uses the Extended Barrowman method to estimate aerodynamic forces from the modeled rocket geometry, rather than directly calculating airflow around the boat tail like in CFD (13, 14). Therefore, flow behavior such as separation and reattachment suggested to reduce base drag are not explicitly modeled.

To reduce differences caused by environmental conditions, the OpenRocket simulations were configured using the launch site's location and atmospheric conditions recorded on the day of testing. Therefore, differences in temperature, pressure, air density, and elevation were reduced between the experimental and simulated conditions. However, flight effects such as wind, rocket orientation, manufacturing tolerances, surface roughness, and other inconsistencies may still contribute to differences between the simulated and experimental flight behavior (12, 13).

The coast phase acceleration and velocity profiles further support the lower drag measured for the 14° configuration. As shown in Figures 3 and 4, the 14° rocket experienced a lower deceleration and lost velocity more slowly than the other configurations throughout the analysis interval. Figure 5 similarly shows that the 14° configuration's calculated drag coefficient generally remained lowest across the entire 15 - 28 m/s velocity range. Therefore, the lower mean drag coefficient of the 14° boat tail was not caused by a single portion of the analyzed coast interval but was observed throughout the entire phase.

A possible explanation for the experimental performance of the 14° boat tail is the separation and reattachment of boundary airflow as described in previous computational and experimental research (3, 11). At taper angles near 14°, the boundary layer may initially separate from the boat tail surface before reattaching further down the boat tail, forming a separation bubble. This can reduce the size of the low pressure wake behind the rocket while avoiding the larger wake caused by complete flow separation at higher taper angles (3, 11). The considerably lower drag coefficient measured for the 14° configuration is consistent with this mechanism. However, because the experiment measured the motion of the rocket, rather than visualizing the airflow, the formation of a separation bubble cannot be confirmed from the experimental data. The difference between the OpenRocket prediction and experimental result

may further indicate that aerodynamic behavior occurring during actual flight may not be completely represented by OpenRocket's simplified aerodynamic model.

The 7° and 21° boat tails showed different behavior compared to the 14° configuration. Experimentally, the 7° boat tail produced a mean drag coefficient of 0.673 ± 0.016 , approximately 1.6% greater than the 0° baseline. However, the difference of 0.010 between the two configurations was smaller than their propagated measurement uncertainties of 0.016. Therefore, this experiment does not provide strong evidence that the 7° configuration performed differently from the baseline. OpenRocket predicted a 5.7% reduction in drag coefficient for the 7° configuration, making it the lowest simulated drag coefficient, although its simulated value was very similar to that of the 14° configuration.

The 21° boat tail produced a mean experimental drag coefficient of 0.572 ± 0.016 , an approximately 13.7% reduction from the baseline, yet considerably higher than the 14° configuration. This result is consistent with previous research showing increased flow separation at steeper taper angles (3, 4). At 21°, the boundary layer may be less capable of reattaching to the highly tapered boat tail surface, increasing the low pressure zone size relative to the 14° boat tail. Similarly, OpenRocket predicted the 21° taper angle to provide less of a reduction to drag coefficient compared to the 14° configuration.

Several limitations of this experiment affect the interpretation of these results. Most importantly, only one experimental flight was conducted for each boat tail. Although hundreds of acceleration measurements were collected during each flight, they represent samples from a single launch rather than independent trials. Differences in wind, launch trajectory, rocket orientation, or other atmospheric conditions could therefore influence the measured differences between configurations. In addition, velocity was determined by integrating the accelerometer measurements, meaning that measurement uncertainty in acceleration can propagate into velocity, and therefore into the calculated drag coefficient. Furthermore, the standard deviation of drag coefficient during each coast phase represents the amount the calculated drag coefficient varied throughout that individual flight, and is not the measurement uncertainty of the accelerometer. Differences between the OpenRocket predictions and experimental measurements may also result from factors that cannot be represented in an idealized simulation. Previous research has identified factors such as surface roughness, fin imperfections, wind induced drift, and other effects as reasons for differences between simulated and real flight performance (12). Finally, while the 14° configuration generally maintained a lower drag coefficient throughout the coast phase interval, variation within each flight reveals that drag coefficient was not completely constant with velocity. Propagated drag coefficient uncertainty also increased as velocity decreased because velocity appears as a squared term in the denominator of the drag coefficient calculation and aerodynamic deceleration becomes smaller at lower velocities. This may have contributed to the increased scatter observed near the lower end of the 15 - 28 m/s interval. This reinforces the importance of comparing all configurations over the same velocity range and of conducting repeated flights in future work.

Despite these limitations, the results indicate that boat tail taper angle can substantially affect the aerodynamic performance of a model rocket during its coast phase. Of the four boat tails tested, the 14° configuration produced the lowest experimental mean drag coefficient and provided a reduction in drag coefficient by approximately 38.7% relative to the baseline 0° configuration. This result agrees with the range of optimal boat tail angles predicted by previous subsonic CFD and wind tunnel research, suggesting that similar aerodynamic effects observed

in literature may also be present during actual flight. More broadly, model rockets offer a relatively low cost and accessible platform for experimentally testing aerodynamic concepts that would be significantly more expensive to investigate using larger launch vehicles. The aerodynamic benefits of rear tapering have also been demonstrated at substantially different scales and geometries, including box shaped ground vehicles and SUVs (7, 8). Small scale experiments such as this can therefore be used to identify aerodynamic trends and promising geometries before conducting more complex wind tunnel, CFD, or larger scale testing.

Future research should conduct multiple flights for each boat tail configuration to confirm consistency and reduce the effect of launch variations. Furthermore, testing additional taper angles, specifically between 12° and 18° , would allow the experimentally optimal taper angle to be determined more precisely. The experiment could also be improved through measurements of rocket orientation and local wind conditions, as well as direct comparisons with CFD or wind tunnel flow measurements. Similarly, previous research has indicated that including factors such as wind and launch angle can help reduce the gap between simulated and real flight behavior (12). To determine how well the observed trend scales beyond model rockets, similar boat tail configurations could be tested on vehicles of increasing size, while maintaining similar geometric ratios. The results could then be compared across Reynolds numbers to determine whether the same relationship between taper angle and base drag reduction continues as vehicle size and velocity increase. Therefore, rather than directly predicting the performance of a full scale launch vehicle, this type of model rocket experiment can provide a relatively inexpensive first step for identifying aerodynamic configurations that justify further investigation at larger scales. Overall, the results identify the 14° boat tail as the most aerodynamically efficient of the 4 configurations tested and demonstrate the potential for small scale free flight experiments to analyze drag reduction methods under actual flight conditions.

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