Flight Performance of a Small, Low-Altitude Rocket

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SMALL rockets can inexpensively aid a number of scientific and operational requirements, such as meteorological sampling, payload component tests, tracking and telemetry systems checkout, and training in the launching and tracking of sounding rockets. The 2.75-in.-diam Folding Fin Aircraft Rocket (FFAR)\textsuperscript{1} has served as a ground-launched radar test rocket for several years at the NASA Wallops Station. The standard inert rocket head has been modified to carry pyrotechnic flares and a smoke-producing chemical to aid radar acquisition using a manual optical sight. In addition, the rocket has been flown with low-drag nose cones, rocket heads weighing 3.8 to 25 lb, and 1-in.-diam separable darts. Other organizations have used it for component tests\textsuperscript{2} and as a booster for nonwithstanding darts and powered stages.\textsuperscript{3,4}

Theoretical Trajectories

The performance characteristics of the 2.75-in. FFAR have been determined using a two-dimensional particle trajectory program. The trajectory's equations of motion are written in an intrinsic coordinate system assuming a spherical, non-rotating earth and employing a modified Euler integration with varying time increment. Exponential density and linear sound speed variations with altitude, based on the 1959 ARDC (Air Research and Development Command) Model Atmosphere, are employed.

Basic drag and thrust curves for the 4-ft long standard configuration weighing 17 lb with a 5.7-lb rocket head were obtained from the flight testing of several rounds. Drag deceleration during coasting flight, as indicated by a Model 10A velocimeter (Doppler radar) and an FPS-16 radar, was used to find the variation of drag coefficient with Mach number in the transonic and supersonic regimes. Deceleration data during the subsonic portion of the flight were too noisy to be useful; consequently, the drag coefficient was obtained by fitting computed trajectories to the flight-test results, varying the drag coefficient until the computed velocity and altitude profiles were essentially the same as the observed values. In a similar fashion, the thrust, which is assumed constant, was varied to fit the burnout velocity and time indicated by flight test. It was assumed that the rocket is launched at sea level and accelerates to 106 fps within its launcher before entering free flight.

The velocity and altitude profiles of the standard configuration, launched at 80° to the horizontal, are shown in Fig. 1. The maximum velocity of 2415 fps corresponds to a Mach number of 2.18 and a dynamic pressure of 6500 psf. Acceleration varies from 40 to 48g during burning, dropping abruptly to -16g at burnout, 1.7 sec after ignition. The rocket becomes supersonic 0.85 sec after launch, dropping below sonic velocity at 7.4 sec. During the coast, the rocket spends 4 sec decelerating through the transonic range from $M = 1.2$ to 0.8 at altitudes from 7000 to 12,000 ft, whereas the dynamic pressure drops from 1600 to 650 psf. The velocity profile for other launch angles is similar, with higher velocity at apogee as the launch angle is decreased. Apogee is reached 29 sec after launch, and impact occurs 41 sec later.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard deviation</th>
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</thead>
<tbody>
<tr>
<td>Apogee altitude, ft</td>
<td>19,151</td>
<td>592</td>
</tr>
<tr>
<td>Impact range, ft</td>
<td>12,740</td>
<td>1968</td>
</tr>
<tr>
<td>Impact time, sec</td>
<td>70.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Effective launch elevation angle, deg</td>
<td>78.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Azimuth shift, deg</td>
<td>8.4</td>
<td>18.3</td>
</tr>
</tbody>
</table>

Fig. 1 Velocity and altitude profiles with standard 5.7-lb rocket head, launched at 80° at sea level.

Fig. 2 Apogee altitude, apogee range, and impact range of the standard rocket for launch angles of 70° to 85°.
Apogee altitude, apogee range, and impact range are plotted as functions of launch angle in Fig. 2; representative altitude vs range plots are presented in Fig. 3. The trajectories are nearly parabolic (as would be predicted with the flat-earth, drag-free assumption), but apogee altitude is a function of launch angle when drag is neglected, because aerodynamic effects are significant over the entire flight. When the standard aerodynamic configuration is launched at 90°, the maximum apogee altitude of 19,500 ft occurs with a rocket head weight of 7 lb, as shown in Fig. 4. Higher burnout velocities associated with lower head weights are accompanied by even greater drag losses, whereas burnout velocities associated with higher head weights are too low to overcome gravity losses.

Wind effects on the standard rocket’s flight path have been calculated using a 6-degree-of-freedom trajectory. They are assumed to end at motor burnout since, for most sounding rockets, thrust deflections because of “weathercocking” produce larger overall effects than the wind drift that occurs throughout the flight. Thirty-five percent of the wind effects during burning occur below an altitude of 325 ft; thus, meteorological towers at most rocket test ranges can supply data adequate for a major portion of the wind-weighting. Because the winds at low altitude are subject to short period variations, wind measurements, calculations, and launch settings must be made within a few minutes. As long as the wind-deflected impact point lies within a safe area, it may be satisfactory to omit the last step. The linearized uniform wind correction used to relate the trajectory deflection to the “ballistic” or weighted-average wind velocity is 0.23 deg/ft/sec at burnout, corresponding to an impact range change of 11.8 ft/ft. Experimental values of impact range indicate that the wind drift is larger than was anticipated; therefore, precise wind-weighting requires consideration of winds up to the rocket’s peak altitude.

**Flight-Test Results**

Twenty-eight rockets of various configurations, launched from a 3/4-ft tube mounted on an adjustable frame, were tracked by pulse and Doppler radar. Winds were measured, but launcher settings were not corrected for wind effects. Seven rockets had standard heads and were launched at 80°, yielding the statistics of Table 1. The means and standard deviations reflect variations due to winds as well as vehicle dispersion. For example, the mean effective launch angle of 78.1°, rather than the 80° set in the launcher, would indicate a mean ballistic headwind of 8 fps, assuming negligible systematic errors in the launcher and velocity. The 1300-ft difference in mean and theoretical impact ranges (for the 78.1° launch angle) is largely because of downrange drift caused by upper air winds which predominate at the launch site. Although percentage dispersions are large, the magnitudes should cause no concern for the experimenter or the range safety officer.

In order to compare apogee altitude of rockets with varying head weights to the computed curve of Fig. 4, launch angle dispersion was corrected with the assumption that the trajectories are nearly parabolic. The discrepancies between the curve and 3.8-, 5.7-, 20-, and 25-lb cases are the result of changes in aerodynamics. The 3.8-lb rocket heads were 5.1 right circular cones, whereas two 5.7-lb heads were 5.1 tangent ogives; as these rockets had 5% less drag than normal, the increase in apogee altitude is expected. Similarly, the 20- and 25-lb heads possessed higher drag than usual, and their performance was reduced accordingly.

If the 2.75-in. FFAR is used to boost a slender, separable dart to high velocity, maximum altitude can be increased substantially, as the drag-to-mass ratio of the final stage is reduced greatly. For the Wallops tests, 1-in. diam darts were fitted to the motor with a special adapter; they were held in place during boost by thrust acceleration and separated by differential drag deceleration at motor burnout. Four darts weighing 4 and 6 lb were launched at 80°, reaching altitudes from 36,120 to 36,750 ft. Although this combination performed well, there was no immediate need at Wallops for a vehicle with this payload-altitude characteristic, and the flight-test program was brought to a close.

**Conclusion**

A 2.75-in. diam FFAR launched at sea level is capable of carrying loads of 3.8 to 25 lb to peak altitudes from 20,000 to 12,000 ft. These altitudes can be roughly doubled if the rocket is used to boost a slender, separable dart containing the payload. Although percentage dispersions of trajectory parameters are large, dispersion magnitudes are not likely to compromise safety or mission objectives.

**References**