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Launch Competition for Rocket Propulsion Education*

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A competition involving launches of solid propellant 'model rockets' has been developed to aid in the education of rocket propulsion fundamentals. Students are organized into teams whose goal is to provide a complete modeling of the rocket's trajectory assuming the body remains in a single plane. The project not only exposes students to state-of-the-art experimental techniques for measuring thrust and drag, but also reinforces the importance of team coordination in solving problems. Students have responded positively to this project, which heightens understanding of basic propulsion concepts as well as many of the elements of an actual rocket launch.

INTRODUCTION

AEROSPACE and mechanical engineering schools typically utilize a classroom lecture format to teach the fundamentals of both air-breathing and rocket propulsion systems. It is often difficult to provide meaningful classroom demonstrations and laboratory projects related to propulsion systems due not only to their complexity, but also because of the hazardous propellants which may be involved. To address these issues, we have recently developed a rocket launch competition which is held as an integral part of our undergraduate rocket propulsion course (catalogue no. AAE 439). To date, this competition has been held a total of eight times dating back to the Fall of 1991. In this paper, we shall describe the elements and organization of this competition as well as lessons learned as a result of this experience base.

The competition focuses on the use of high-power model rockets as a means of demonstrating rocket propulsion and trajectory principles to the class. The class is divided into Launch Teams which consist of 5–7 members as well as a Range Safety Team. Each Launch Team is responsible for the construction and testing of a model rocket with the goal of providing a two-dimensional flight simulation capability which is utilized on launch day. The Range Safety Team acts as an independent organization responsible for coordination of all launch activities. We feel that this organization is important in that it promotes coordination between various team members, who must function as a portion of a larger group. Many lecture courses focus solely on individual performance as a measure of competence in a given subject, which does not permit the development of the interpersonal skills required in most jobs.

Typically, we have 2–4 Launch Teams and a Range Safety Team within a given class. Efforts related to the project span about 2 weeks; normal class lectures are held during this timeframe, so the bulk of the activities are conducted outside of class. A limited amount of time (5–10 min) is provided at the end of several lectures to allow teams to coordinate activities. In the following sections, we provide detailed descriptions of team activities and the structure of the launch competition itself.

LAUNCH COMPETITION RULES AND GUIDELINES

Typically we have used the 'Big Brute' model rocket kit manufactured by North Coast Rocketry [1] for the launch competition. This kit was selected based on its moderate cost, ease of manufacture, and high drag characteristics. A schematic of the model rocket is shown in Fig. 1. Each launch team is responsible for the construction of their own rocket: significant modifications to the weight or aerodynamic characteristics are not allowed.

Through aerodynamic and propulsion testing, and the development of a trajectory model, each team gains the capability to simulate the complex

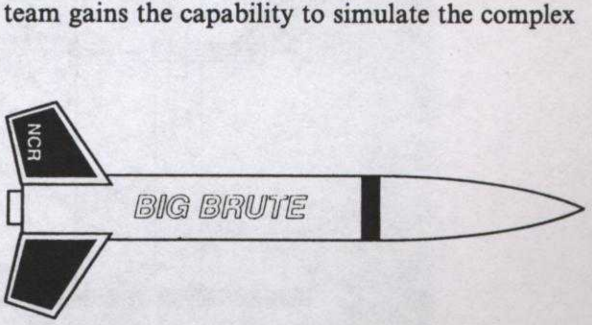

Fig. 1. Schematic of the 'Big Brute' model rocket manufactured by North Coast Rocketry (89 cm in length with 10.2 cm on body diameter).

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launch trajectory of its rocket (as described in the following sections). On launch day, two helium-filled balloons are launched to provide average wind speed estimates to each team. Using this information (as well as all test data), each team provides a prediction of the angle of the launch rod required to have the rocket land at the site of the launch. The launch rod is oriented in the plane of the average wind vector (to the greater extent possible). In addition, each team provides a prediction of the rocket's altitude at the time of parachute deployment for the launch angle they have selected.

Two series of launches are conducted and measurements of landing position error and altitude error are provided by the independent Range Safety Team. Launch Teams are ranked based on their relative standing for each of these two measurements. Assuming four teams, first place in either category is awarded 10 points; followed by 7, 5 and 3 points for second, third and fourth place, respectively. The team with the most points at the end of both series of launches is declared the winner. This team gets their picture placed on our 'Rocketeers of the Year' plaque placed prominently near our student lounge. In the event of a tie, the team with the most accurate landing of all series of launches is declared the winner.

LAUNCH TEAM ORGANIZATION

Each launch team is organized into groups which perform the various functions required to support the launch competition. Each team has a Team Leader who is responsible for coordinating the activities of the various groups. In addition, the Team Leader is responsible for construction of the model rocket. This individual also provides a useful interface between the instructor and the individual teams. As the launch date nears, the Team Leader typically supports work being conducted by other groups. Finally, this person is responsible for coordinating a team report following the competition. Results from reports are typically briefed to the class by the various Team Leaders at the end of the competition.

The Team Leader is supported by an Aerodynamics Group, a Propulsion Group and a Trajectory Group. These groups perform the testing and analysis required to support the launch day predictions. The following subsections provide a detailed description of the activities of each of these three groups.

Aerodynamics Group

The Aerodynamics Group typically consists of one or two people who are responsible for defining vehicle drag during both the launch/coast and parachute recovery phases of the flight. A significant effort was required to obtain reliable drag measurements using existing wind tunnel facilities at Purdue [2]. One of the main challenges here is due to the fact that the total drag force is only a few ounces under the dynamic pressure conditions attainable to the low-speed wind tunnels.

Initial drag measurements were obtained using 1.2 × 1.8 m closed-loop wind tunnel at the Aerospace Science lab. Since this tunnel is designed to reach speeds of 130 m/s, the trapezoidal balance in this tunnel was designed for larger objects, and we had great difficulty in resolving the small drag force associated with this device. For this reason,

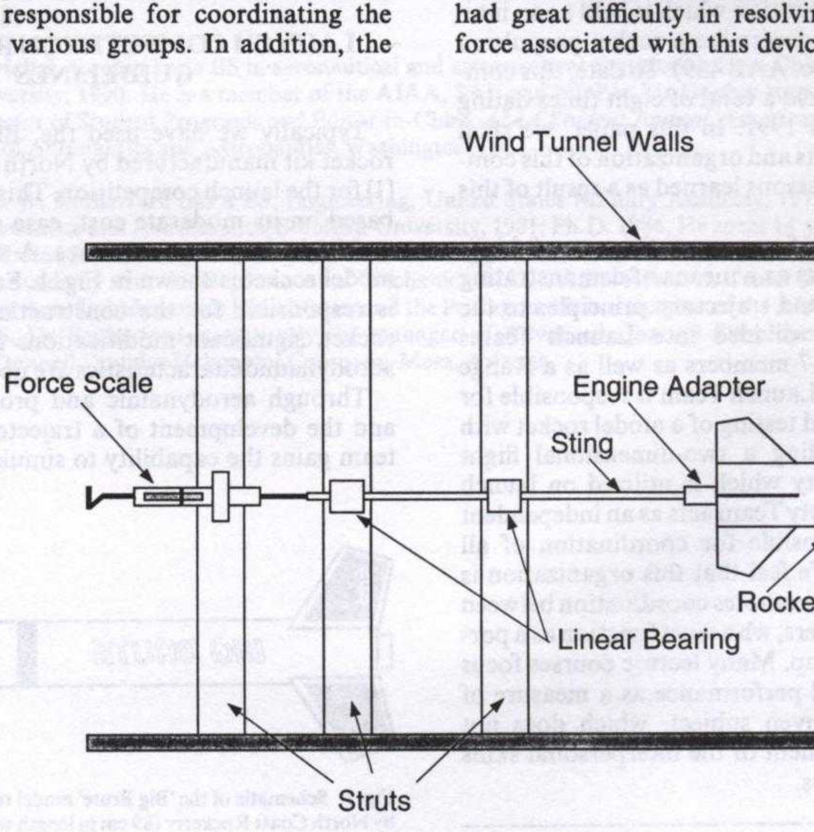

Fig. 2. Schematic of drag measurement apparatus.

we decided to develop a new balance for this project, and to install this balance in a smaller, 46 cm diameter, open-loop wind tunnel. This tunnel has a maximum velocity of 24 m/s. Blockage effects are also a concern, since the 10.2 cm diameter rockets create a 5% flow blockage of the tunnel. While this is on the upper end of allowable flow blockage, it is deemed acceptable for the student project.

Since the previous use of an existing trapezoidal force balance did not provide adequate results in this tunnel, a simple sting-mounted balance was devised. As shown schematically in Fig. 2, the balance consists of three support struts that hold two linear bearings and the force scale. The sting has an adapter fitting that mounts into the motor case to allow quick and easy conversion to rockets with different motor diameters. The sting glides through the two bearings before impacting the push rod of the scale. The scale was sized to the tunnel with preliminary calculations [3] and a 100 g scale with 4 g divisions was selected. The full range of the scale corresponds to roughly 95% of the maximum tunnel speed. With this system, measurements of drag coefficient can be made for Reynolds numbers from 60 000 to 170 000 based on the diameter of the 'Big Brute' rockets. An image of the rocket mounted on the sting inside the wind tunnel is shown in Fig. 3.

The results of three experiments are compiled in Fig. 4, where the drag coefficient is plotted versus the Reynolds number. Initially, we were concerned about the trend of the data, believing that for the Reynolds number range tested, the characteristic transition from laminar to turbulent flow would be observed. However, the consistency of the results indicated that the flow is turbulent over the full range studied. This is most likely due to tripping of the boundary layer at the junction of the nose cone with the body.

While the new balance yields more accurate drag measurements, students face the challenge of extrapolating the data fro wind tunnel Reynolds numbers up to the maximum flight value of about 500 000. One possible extrapolation of the data with a logarithmic curvefit is shown in Fig. 4. Students are also given an alternative to the wind tunnel measurement by using an analytical procedure [4] (with associated empirical data). A class handout is provided which serves as an aid in developing this procedure. In the past, many groups resorted to the analytical calculation because of large uncertainties in the experimental measurements. However, with the increased sensitivity offered by the spring balance design described above, the measurements are now used by most groups.

With respect to flight under parachute recovery, students have shown considerable innovation in trying to define the drag of the rocket. A minimum amount of instructor interaction is provided here in favor of the students searching for their own solution to this problem. Students are generally referred to Hoerner's book [3] as a means of performing analytical calculations. As described in the Trajectory Group section below, most Aerodynamics Groups presume that the lateral force coefficient of the body under parachute is high enough such that the body rapidly begins to translate horizontally at the measured wind speed. Using this assumption, the bulk of the efforts are confined to the vertical force balance between parachute drag and the weight of the rocket.

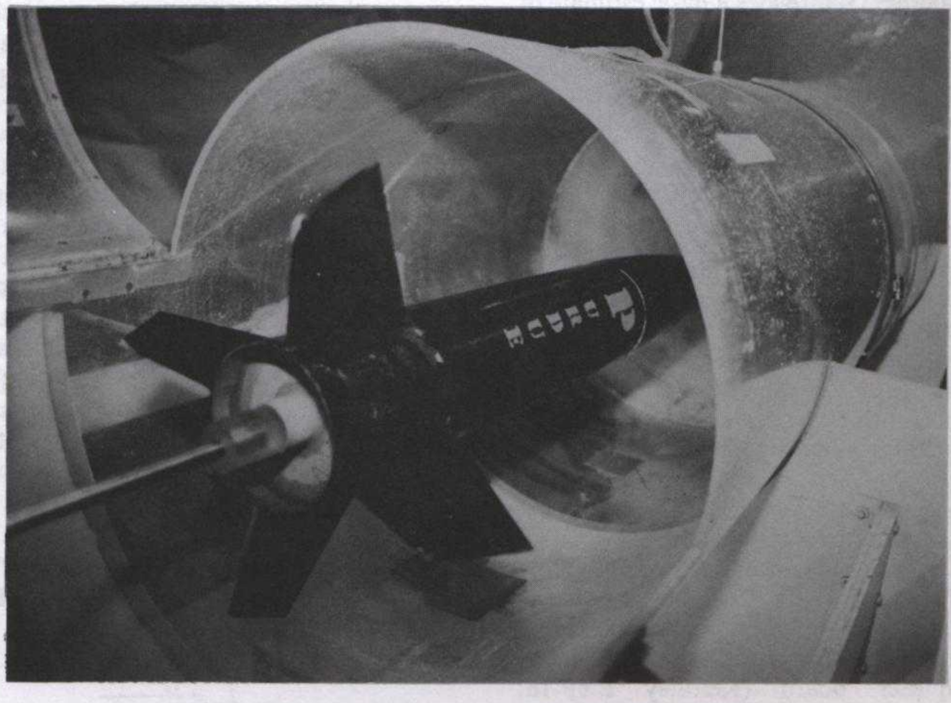

Fig. 3. Photo of rocket installed in drag measurement apparatus.

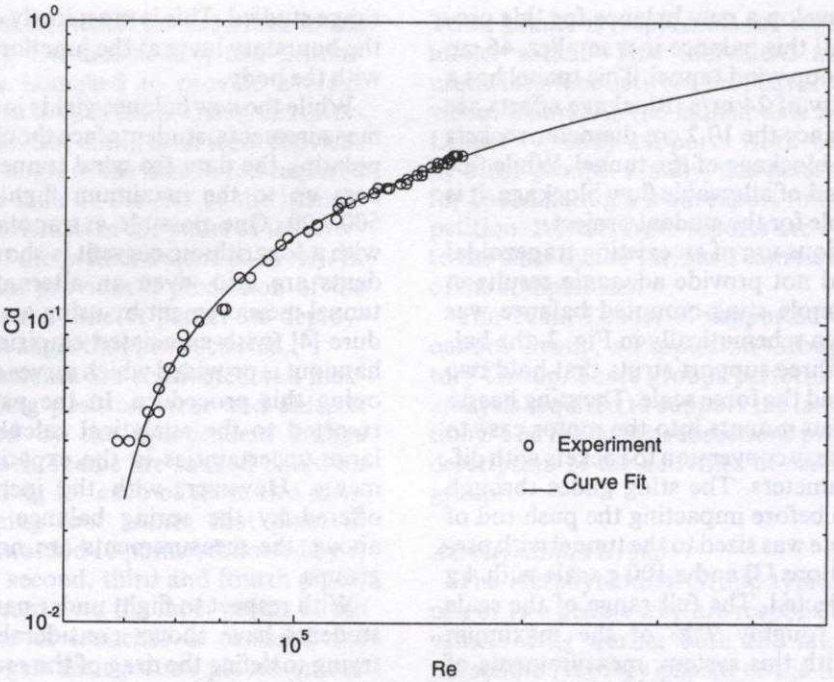

Fig. 4. Measured drag characteristics of 'Big Brute' rocket.

Most commonly, the students perform a drop test (from various university buildings, parking structures, etc.) to determine experimentally the terminal velocity, and hence the drag, under parachute. Various degrees of sophistication have been employed here; many groups understand that the accelerating portion of the drop test should somehow be eliminated from the measurements. Other groups have attempted to measure parachute drag by attaching the chute to a scale and driving at fixed speeds in their car. Most groups have derived drag coefficients of between 1.5 and 2.0 using this approach. Hoerner [3] provides a basic estimate of 1.4 which is considerably lower than the value used by many groups. These coefficients are based on a reference area assuming an effective chute diameter of 40.6 cm—two-thirds of the geometric diameter of the chute.

Propulsion Group

The Propulsion Group typically consists of one or two people who are responsible for defining engine performance for use in trajectory simulations. A significant development required for this aspect of the project involved the development of a small engine test stand capable of providing thrust measurements for this purpose. Figure 5 presents a schematic of the test stand highlighting major components. The stand itself makes use of a parallelogram-type support system to ensure that the thrust produces pure translation of the upper plate.

The load cell, manufactured by Interface Corporation of Scottsdale, Arizona, has a 220 N maximum force capability and a quoted accuracy of ±0.01%. This device is connected to a signal conditioner/multiplexer board (Keithley EXP-16) which interfaces with an analog/digital converter (Keithley DAS-8) installed in a standard personal computer. While most of the software required for the use of the analog/digital interface was included, a teaching assistant also created programs to set up the calibration of the load cell. This calibration is performed by hanging known weights from a pulley which was mounted on the end of the thrust stand itself. A photo of a typical test, highlighting the location of the pulley and the engine, is shown in Fig. 6. Note the Mach diamonds in the highly underexpanded exhaust of the motor.

Members of the Propulsion Group are able to operate the test stand with the use of a short handout describing the facility operation and a little help from the teaching assistant. Each group tests two engines to determine an average thrust history for use in predictions. Typically, we have used the 'F' class engines manufactured by Aerotech Industries [5]. Motor pre- and postfire weights (W_o and W_f respectively), are recorded for use in predicting specific impulse and the rocket's weight history. A typical thrust measurement is comparable to the manufacturer's prediction in Fig. 7. Note that very little 'ringing' is present in the measured data which indicates that the natural frequencies of vibration for the stand lie above the range generated by the thrust pulse. Independent measurements from various groups indicate good repeatability in total impulse (integral under the thrust curve).

The average delivered specific impulse I_{sp} is obtained in a standard fashion by integrating the measured thrust (F) history:

$$I_{sp} = \frac{\int_0^{t_b} F \, dt}{W_0 - W_f} \tag{1}$$

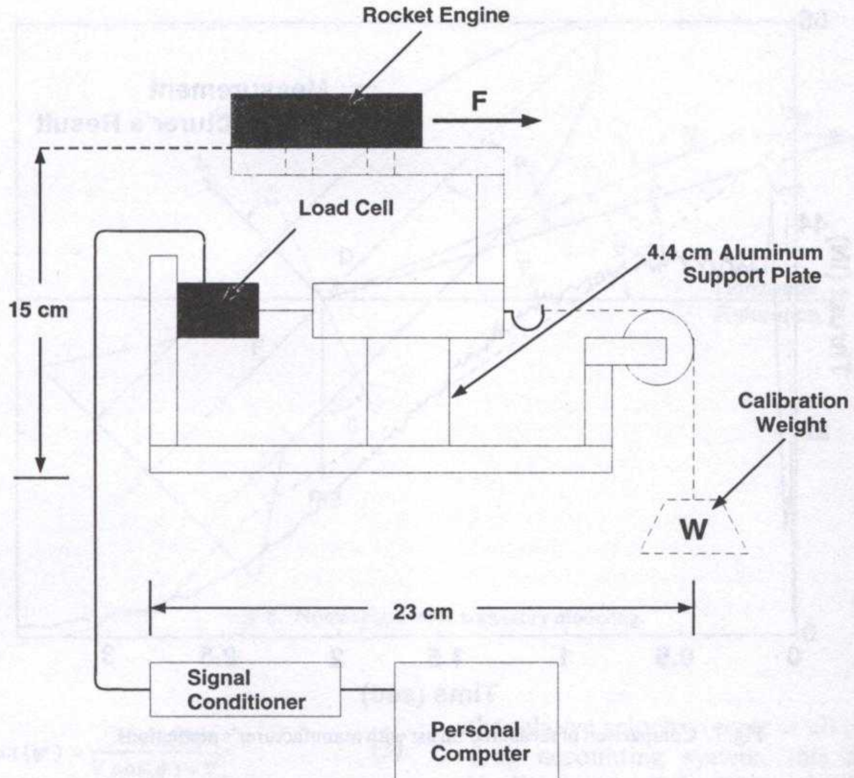

Fig. 5. Schematic of thrust measurement apparatus.

where t_b is the total burning duration. The students generally measure values of I_{sp} to be around 160 s, which is well below the manufacturer quoted value of 197 s.

Data from a given test is typically recorded at 200 samples. Students within the Propulsion Group are generally somewhat daunted by this rather large amount of data in that most homework or project assignments involve very few data points. By using this state-of-the-art thrust measurement

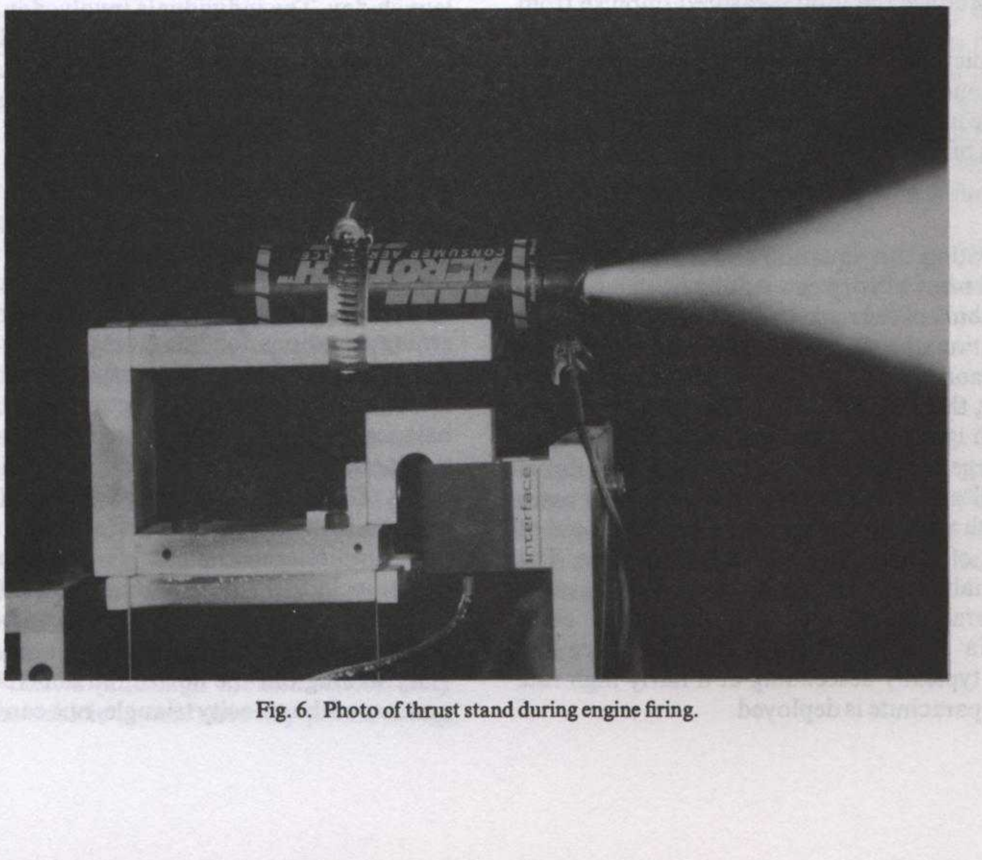

Fig. 6. Photo of thrust stand during engine firing.

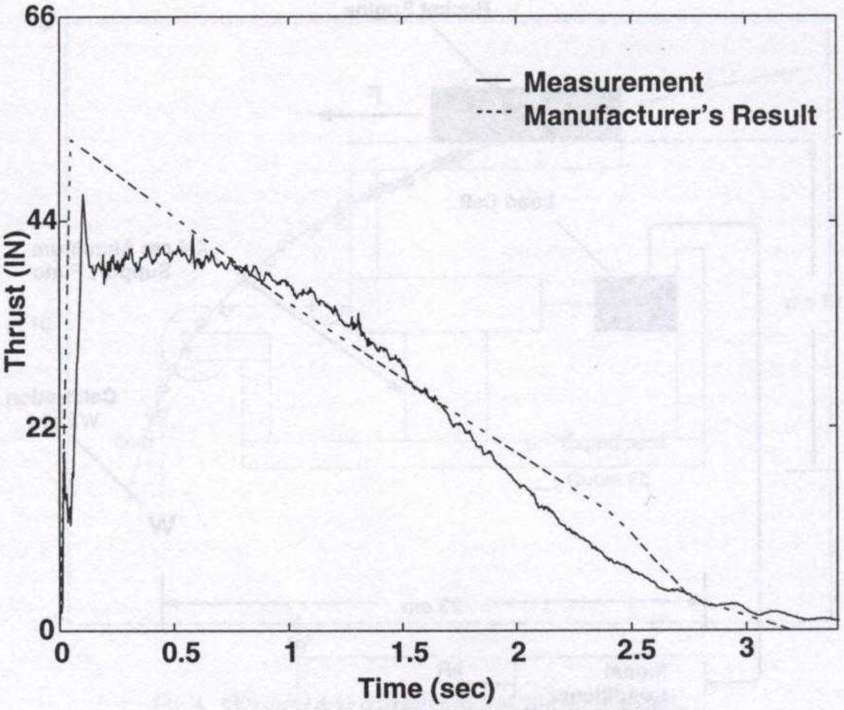

Fig. 7. Comparison of measured thrust with manufacturer's predictions.

technique, the students gain an appreciation of the volumes of data encountered in realistic tests performed in industry. Most groups end up averaging data down to a lower sample rate, or more commonly they simply apply a curve-fit to the results. From an instructional standpoint, we provide very limited interaction here, preferring to let the students figure things out for themselves. Students are cautioned that their curve-fits (if used) should accurately reproduce the total measured impulse from the firing.

To predict the weight history for the rocket, students assume that the measured I_{sp} value is constant so that the instantaneous flowrate follows from the definition of I_{sp}.

$$\dot{W} = F/I_{sp} \tag{2}$$

By integrating this equation to various times, the expended mass history can readily be determined. Since the bulk of the rocket's flight is under a coasting condition, the shape of the massflow curve has only a minor effect on the overall trajectory.

Finally, the Propulsion Group must measure the time from ignition (or burnout) at which the ejection charge deploys the parachute. The thrust stand will actually pick up the small force associated with the ejection charge, which is sent out of the front of the engine to deploy the chute. The large variability in this parameter (as measured over several classes) is one of the major error sources in the trajectory predictions since the rocket is typically descending at a fairly high rate when the parachute is deployed.

Trajectory Group

The Trajectory Group generally consists of two or three people who have the responsibility of creating a two-dimensional trajectory simulation of the rocket flight. In many respects, this group has the biggest challenge in that they must coordinate inputs from the Aerodynamics and Propulsion Groups, and their predictions serve as a basis for the launch angles and altitudes predicted on launch day. The individuals involved in this group often make some of the most outstanding efforts associated with the project. In many cases, Team Leaders choose to help this group substantially due to the importance of their results.

The basis for the two-dimensional simulation actually stems from a homework assignment which is completed prior to the project. Each student in the class is required to develop this simulation which includes the effect of a head-wind, but does not account for parachute deployment. The governing equations for this situation are a modified form of those generated in Sutton [6], which results from the use of Newton's second law on the force balance shown in Fig. 8. Here, V, V_{rel} and V_w are the inertial, relative and wind velocities, respectively. The quantity θ is the horizontal reference angle, α is the angle of attack and ψ is the vehicle centerline reference angle. Forces acting on the rocket include thrust (F), drag (D), life (L) and the rocket's weight (Mg), all of which can be functions of time.

By writing out the horizontal and vertical components of the velocity triangle, one can show:

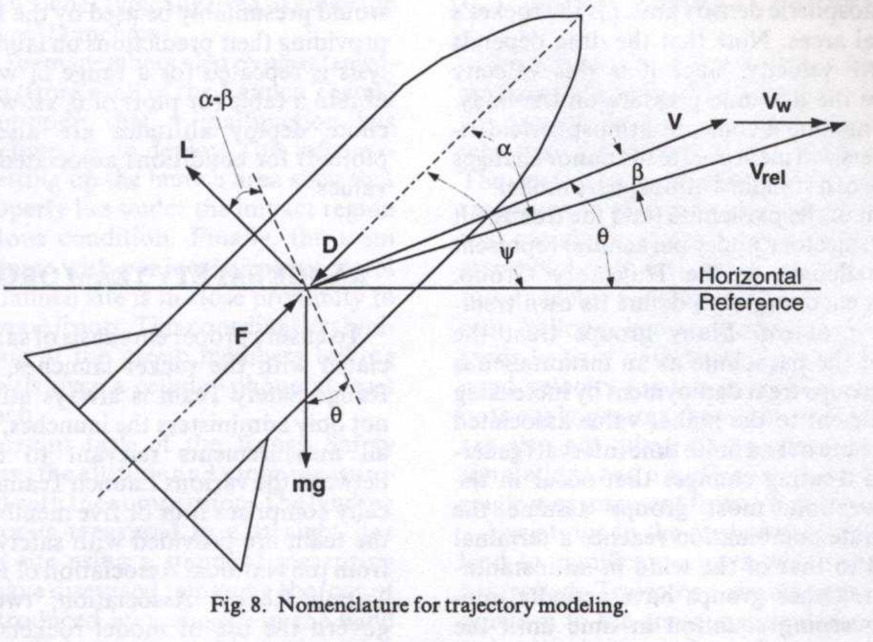

Fig. 8. Nomenclature for trajectory modeling.

$$\tan(\psi) = \frac{V\sin(\theta)}{V\cos(\theta) + V_w} \tag{3}$$

which relates ψ to θ and the velocities. From Fig. 5, β can be related to the other three angles:

$$\beta = \alpha + \theta - \psi \tag{4}$$

By considering a force balance along the vehicle centerline, Newton's second law gives:

$$M\frac{\mathrm{d}V}{\mathrm{d}t} = (F - D)\cos(\psi - \theta) - L\sin(\psi - \theta) - Mg\sin(\theta) \tag{5}$$

Similarly, in the direction perpendicular to the axis of the rocket, we have:

$$MV\frac{\mathrm{d}\theta}{\mathrm{d}t} = (F - D)\sin(\psi - \theta) - L\cos(\psi - \theta) - Mg\cos(\theta) \tag{6}$$

If the rocket is still on the launch rod, equation (6) is replaced by $\theta = \theta_1$ where θ_1 is the angle of the launch rod itself.

Noting that lift and drag are typically written as functions of the angle of attack, equations (3)–(6) represent four relationships for the five unknowns $\alpha, \beta, \theta, \psi$ and V since V_{rel} can be determined from trigonometry if V is known. To determine the angle of attack, we would also need to consider a moment balance about the vehicle's center of gravity. Since an aerodynamic moment coefficient would be required for this moment balance, we have assumed that the rocket operates under a ballistic trajectory defined by $\alpha = 0$. Physically, this assumption implies that the rocket has a very low moment of inertia (and high moment coefficient) such that the vehicle instantaneously points along the relative velocity vector at all times. In our lift/drag accounting system, this assumption also implies that $L = 0$ since the rocket has no lifting surface at zero angle of attack.

A ballistic trajectory simulation is prudent when the vehicle is at moderate or high velocities, since the fins will generate large restoring moments in the event that an angle of attack develops. However, near liftoff, where speeds are low, an alternative formulation is typically utilized by the Trajectory Group. Most groups have chosen to artificially extend the launch rod (to a total length of 3–6 m) to account for the fact that the vehicle cannot instantaneously respond to the crosswind upon leaving the rod. Other groups have specified a 'pitch rate' to use until the rocket aligns itself with the relative wind. Once again, minimal instructor interaction occurs here in favor of each group finding a suitable alternative on its own. Many groups fail to realize that the analysis is fairly sensitive to the selected length of launch rod—a definite shortcoming in the present approach.

As mentioned above, equations (3)–(6) are provided in a homework assignment which is given to all students prior to the start of the project. Equations (5) and (6) are typically integrated using Huen's method [7], a second-order scheme which is actually coded by the students. Results from this assignment serve as a starting point for those within the Trajectory Group. Vehicle thrust and mass histories are provided by the Propulsion Group, while the Aerodynamics Group provides a drag coefficient, C_{D}, which permits the calculation of drag via the standard expression:

$$D = C_{\mathrm{D}}\frac{1}{2}\rho V_{\mathrm{rel}}^2 A \tag{7}$$

where p is atmospheric density and A is the rocket's cross-sectional areas. Note that the drag depends on the *relative* velocity, since it is this velocity which dictates the dynamic pressure on the body. Most groups assume a constant atmospheric density, while others will incorporate the minor changes dictates by use of a standard atmosphere model.

Deployment of the parachute (and the treatment of the rocket trajectory under parachute) represent significant challenges to the Trajectory Group. Each group is encouraged to define its own treatment of this problem. Many groups treat the deployment of the parachute as an instantaneous event. Other groups treat deployment by increasing the drag coefficient to the higher value associated with the parachute over a finite time interval (generally <1 s). In treating changes that occur in the transverse direction, most groups assume the rocket/parachute combination reaches a terminal velocity equal to that of the wind in an instantaneous manner. Other groups have actually integrated the governing equation in time until the rocket is moving laterally at the assumed wind speed. A similar treatment is employed in the vertical direction in which the rocket rapidly reaches terminal velocity. Once under terminal velocity conditions in both planes, the rocket descends under constant glide slope since the wind speed is assumed to be constant.

Sample trajectory predictions are shown in Fig. 9 for an assumed wind velocity of 5 m/s, assuming the engine thrust shown in Fig. 7 and a drag coefficient of 0.2 for various initial launch angles. A 6 s ejection delay is also assumed in defining these trajectories. From the results in Fig. 9, it is apparent that a θ_1 value of 67° is required to cause the rocket to land at the launch site. This is the value that would presumably be used by the Launch Teams in providing their predictions on launch day. The analysis is repeated for a range of wind velocities to obtain a table (or plot) of θ_1 vs. wind speed. Parachute deploy altitudes are also tabulated (or plotted) for conditions associated with optimal θ_1 values.

RANGE SAFETY TEAM ORGANIZATION

To ensure proper emphasis of safety aspects associated with the rocket launches, an independent Range Safety Team is always utilized. This team not only administers the launches, but also collects all measurements relevant to the competition between the various Launch Teams. The team typically comprises four or five members. Members of the team are provided with safety documentation from the National Association of Rocketry and the Tripoli Rocket Association, two bodies which govern the use of model rockets. In accordance with the regulations described in these sources, observers are placed at least 50 ft. from the launch pad and launch angles >60° are utilized.

Members of the Range Safety Team also request information from Launch Teams regarding the maximum wind velocity which permits the use of launch angles (θ_1) greater than the 60° requirement. Typically, the response to this question yields wind speeds in the 9–11 m/s range. We have been fortunate not to have any launches canceled as a result of this criteria. We also have taken the precaution of building an extended launch rail (1.8 m in length) to reduce oscillations (caused by gusts of wind) which were present in the standard 1.2 m launch rod. The launch rail also facilitates removal

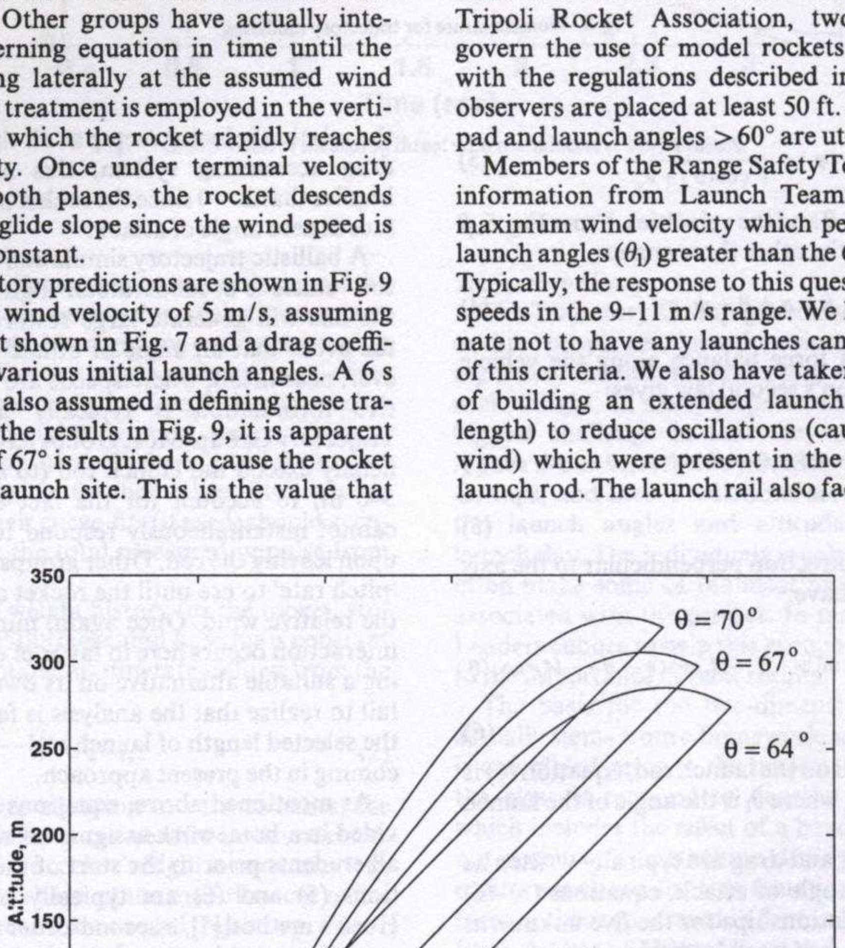

Fig. 9. Typical trajectories: 5 m/s wind speed, $C_D = 0.2$.

of the launch lug which is typically used to guide the rocket for 'rod type' launchers.

Range Safety Team members also request trajectory information (from each of the Launch Teams) under the assumption that a malfunction has caused the parachute not to deploy. This information is used in setting up the launch area such that no people or property lies under the impact region for this anomalous condition. Finally, the team must also coordinate with our local airport control tower since our launch site is in close proximity to the Lafayette Area Airport. This coordination typically involves one of the group members talking with tower officials over a cellular phone at least 2 m prior to launch.

Another important task of the Range Safety Team is to perform the altitude and range measurements associated with the competition. The landing point range error is measured in a straight line from the launch site using a standard measuring tape. While we have discussed removing the 'out of plane' errors introduced by a change in the wind vector during the flight, we have not yet incorporated this change. The altitude measurement is accomplished by triangulation from two sites placed a known distance from the launch pad. By recording both vertical and azimuthal angles at both these sites, two independent height measurements can be obtained. These two measurements are typically averaged to obtain data for the parachute deploy height portion of the competition.

On launch day, Range Safety Team members will typically arrive 1 h prior to the start of the competition. The launch area is laid out and two helium balloons are launched to determine wind speed prior to the competition. Members of the Range Safety Team typically appoint a Safety Officer and a Launch Control Officer (LCO) to preside over the launches. The Safety Officer inspects each rocket to be launched and aids members of the team in installing the igniter and placing the rocket on the launch rail. This individual also contacts the Lafayette Airport control tower to obtain clearance for the launch and verifies that all observers are in safe positions. The LCO is then responsible for coordination of the measurement sites (via walkie-talkie) and initiation of the motor. Other members of the Range Safety team are stationed at the measurement sites and near the launch pad to obtain the data required for the competition.

Though the results depend quite strongly on wind speed, we typically measure altitudes (at parachute deployment) in the range of 120–330 m. A considerable part of this dispersion is due to the high variability in the ejection charge delay; the rocket can be descending at fairly high velocity when ejection occurs so that a small time error leads to a considerable change in altitude. Landing distance errors also depend strongly on wind speed; measurements to date lie in a broad range from 30 m to >600 m. We actually had one launch which went far enough down range to clear the top of a local dormitory (dubbed the Harrison Hall launch by the students).

INSTRUCTIONAL PERSPECTIVE

Each team is required to write a final report summarizing the activities and results associated with the project. We also ask team members to explain why their rocket behaved as it did on launch day. The teams have provided some very thoughtful responses in this area, and most of them realize that variability in the wind is the largest source of error. Not only does the wind speed vary with altitude (a factor not taken into account due to our current balloon launch measurement), but it also tends to vary with time. In several instances, the wind velocity for the second set of launches was noticeably greater than that of the first set. Gusts are also not taken into account in the trajectory simulations and are effectively averaged out by the single measurement from a balloon launch.

Variations in the engine ejection delay can also lead to significant errors which really cannot be controlled. Trajectory simulations are also quite sensitive to the aerodynamic parameters, particularly in the parachute-deployed configuration. Engine performance has shown fairly small variation in tests and is probably one of the smaller error sources.

As a whole, we believe this project is of definite instructional value at the undergraduate level. The students not only gain an appreciation for the multitude of factors affecting the rocket's trajectory, but they also gain some experimental background from propulsion and aerodynamic measurements. They gain more experience working as a team and are allowed to show their creativity in many aspects of the project. In addition, the project serves as a refreshing change during the middle of a semester full of lectures.

Students routinely provide positive written comments regarding the project and end-of-semester course evaluations. They enjoy and appreciate many of the factors noted above, and they often become quite passionate as to why their rocket did or did not finish in first place. It is obvious that the spirit of competition has aroused many students who might not otherwise take an interest in such activities. Former students inevitably ask about the status of the competition and frequently attend launches if they are in town.

CONCLUSIONS

In this paper, we have described a rocket launch competition which is a useful tool for demonstrating rocket propulsion and trajectory fundamentals. Students are exposed to state-of-the-art experimental methods for determining engine performance and vehicle drag. The competition not only serves as a means to introduce fundamental concepts in a project-type atmosphere, but also enables students to learn to function within a group environment. Finally, the project offers an alternative to the typical series of lectures which might normally be used to address issues related to rocket propulsion.

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