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Paper Session IV-B - A Practical Introduction To Aerospace Vehicle Design

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A PRACTICAL INTRODUCTION
TO AEROSPACE VEHICLE DESIGN

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Abstract

This paper is a blueprint for a unique rocket design course taught to senior level students majoring in Astronautical Engineering at the United States Air Force Academy. In the course Aerospace Vehicle Systems Design, cadets are given the opportunity to apply their knowledge of engineering concepts to an aerospace design problem at a practical, hands-on level. As a team, the cadets design, build, test, and launch a rocket powered vehicle. This paper will overview the course, discuss specific requirements expected of the students, and provide information concerning course administration.

Nature of the Course

Aerospace Vehicle Systems Design (hereafter to be referred to as Astro 433) is considered to be the "capstone" course in the Astronautics curriculum. The primary objective of Astro 433 is for the cadets to gain a real appreciation for all aspects of a design problem by experiencing the total design process from the drawing board stage all the way through hardware development and implementation.

Starting with the first lesson, a group of 5 to 9 cadets is assigned to work together as an aerospace contractor to the government (instructors). The ultimate goal of their rocket design company is to launch a small sounding rocket carrying useful payloads on several very-near-earth, suborbital missions. Just as in the "real world," however, the contractor team is constrained by a fixed monetary budget and limited resources. The contractor must map out a plan to successfully accomplish all the technical objectives contracted by the government within the established constraints. The government awards monetary incentives to the contractor for compliance with contractual requirements; it also levies penalties on the contractor for failure to accomplish required tasks.

Overview of the Course

The 42-lesson course is divided into four distinct phases. During the first four lessons we spend time discussing the engineering design process and reviewing case studies of real aerospace design projects. Starting on lesson 5, the cadet rocket design company begins working on its own to design its baseline rocket configuration. From lessons 11 - 16 the cadets work individually to design payloads to be launched on their team's rocket. After these design efforts have been completed, the remainder of the course is dedicated to hardware build-up and testing, eventually culminating with launches from the USAFA Proving Grounds located in the Jack's Valley cadet training area - a safe distance away from the general populace.

Engineering Design Process/Case Studies

Astro 433 generally follows a very loosely structured format. In fact, the instructors formally lecture only during the first two lessons. After reviewing the course syllabus, requirements, and policies on lesson 1, we discuss the engineering design process (EDP) that the cadets should apply throughout the course. The design process we teach consists of these 11 steps:

(1) Identification of Need
(2) Define the Problem
(3) Establish Final Objectives
(4) Collect Data
(5) Establish Constraints
(6) Establish Specifications
(7) Ideate
(8) Conceptualize
(9) Analyze
(10) Experiment/Modify
(11) Communicate Results

We emphasize the importance of those design aspects that young engineers rarely consider their responsibility but which are vital to successful engineering design: economics, schedule, availability, and machinability. We also highlight common pitfalls encountered during the EDP and how they impact the design problem.

After this lesson, the course is a cadet-run show. Their first task as a team is to analyze an AIAA Professional Study Series engineering design case study in light of the EDP and then report their findings in a briefing to the government. Case studies used recently include TRW's FLTSATCOM, General Dynamics' F-16, and Hughes Aircraft's Pioneer Venus. Specifically, the team must address the following items:

I. An overview of the specific system developed, including problems encountered during development.
II. Two typical problems with the EDP and how these errors occurred in the system being studied.
III. Three steps in the design process the development team did well.
IV. Lessons learned from the case study which can be applied to the Astro 433 course.

After their briefing we inform the team that we have noted the problems and successes they addressed in their case study presentation and will watch to see how well they heed these lessons during their team design, rocket build-up, and launch operations.

Rocket System Design

The actual design phase of the course starts on lesson 5 and continues through lesson 16. We have recently instituted a "building block" approach which carries the cadets through the overall rocket vehicle system design process in logical progression. First they analyze and test the small solid motors that will power their team's sounding rocket. Then, as a team, the cadets design their baseline launch vehicle configuration. Lastly, they individually design payloads or rocket subsystems to be flown aboard their team's rocket.

Propulsion

Early in each semester, a designated propulsion engineer from each cadet team is trained to handle and build-up the solid rocket motors his team will use. The Astronautics Lab at Edwards AFB gratuitiously supplies the Academy with unassembled 1.8" x 9.4" polybutadiene/aluminum propellant motors. The cadet propulsion engineer constructs the motors by modifying the propellant grain pattern, sizing the nozzle throat diameter, and installing the end plug and nozzle. Before going into full scale production, the cadets perform static test firings of the motors. The test firings serve several purposes: (1) verify overall engine performance, (2) assure proper motor assembly procedures (burnthroughs have been a definite problem in the past), and (3) provide thrust .vs. time data the team will use to predict rocket performance. The motors produce an average thrust of about 60 lb_f during a nominal 1.6 second burn.

Baseline Rocket Design

The requirements for the baseline rocket configuration are levied on the cadet contractor team via a Statement of Work (SOW). The SOW details those tasks the contractor must accomplish in the rocket's design, development, test, and demonstration. In general, the contractor must design and launch a rocket which will:

(1) Exhibit professional workmanship.
(2) Maintain "zero" roll rate during ascent (zero roll is defined as less than one revolution before apogee).
(3) Attain sufficient altitude to accomodate planned payloads.
(4) Be recovered with minimal damage to the rocket.
(5) Carry a specified number of payloads.

The integrated baseline rocket the contractor designs during this phase consists of a nosecone, recovery system, and propulsion section. The nosecone design must consider ballasting techniques that may be necessary to assure the static stability of the vehicle. The recovery system, typically a parachute deployed by radio control, must be designed such that it will return the rocket to the ground with minimal damage (i.e. the rocket can be reflown within an hour). The propulsion section is a combination motor mount and fin section designed to hold the specified solid rocket motor.

The contractor must analyze its proposed design to prove it will be flightworthy. As a minimum the contractor must analyze the effects of the thrust loads on the vehicle structure and analytically determine the center of gravity (C_g) and center of pressure (C_p) locations to assure static stability of the rocket during ascent. Other areas for analysis may include recovery system dynamics and fin-to-body shear strength.

As part of the design package, the contractor must also include a preliminary performance analysis for the rocket. The contractor is required to develop computer software to predict certain performance parameters such as maximum acceleration, maximum velocity, and apogee altitude.

During the rocket design phase this semester, the government announced a special fly-off competition between the four competing contractor teams. The company whose rocket attains the highest altitude (with successful recovery) on the first launch will be awarded an additional incentive bonus. The purpose of the fly-off is to "encourage" the contractors to consider trade-offs during their design effort which will improve their rocket's performance.

Individual Design Phase

With an understanding of their team's rocket configuration and its predicted performance, the cadets now have the pertinent data available for use when developing their individual design project. As a rule the cadets have total freedom in choosing a payload or rocket subsystem they want to design. Due to time limitations, however, only about a half of the payloads designed actually fly. The contractor recommends to the government which payloads should receive a launch opportunity; the government may approve or disapprove the recommendations (the government often has some "high priority" missions it wants to see fly). Some payloads and subsystems which have been designed in the past are described below:

(1) Steerable Recovery System. One of the members of the Academy's award winning parachute team first designed this subsystem. A square canopy is controlled by servo actuated risers to safely return the rocket back to the launch site (RTLS).

(2) Pitot-Static Tube. A transducer measures differential pressures sensed by a pitot-static tube and sends corresponding voltages to an airborne data acquisition system (DAS). After the mission, the data collected by the DAS is down-loaded and processed to give a velocity .vs. time profile of the rocket's flight.

(3) Apogee Detector. As the rocket pitches over at apogee, a set of mercury switches close an electronic circuit which

initiates the recovery system deployment.

(4) Roll Maneuver. Just after lift-off, a fly wheel is sped up by an electric motor. The resulting torque causes the rocket to roll in the opposite direction of the fly wheel's rotation.

(5) Sun Tracker Control System. A set of photo-diodes placed around the periphery of the rocket body sense the level of incident sunlight. A control signal based on the differential light measurements commands servo actuated canards to steer the rocket towards the sun.

Since the individual design project accounts for more than 40% of the student's grade in the course, their final report is expected to be professional and quite comprehensive. In addition to the design drawings and accompanying analysis, the report must include sections on launch vehicle integration, materials required, assembly instructions, and ground testing.

Build-up/Test/Flight Phase

On lesson 17 the cadets begin meeting regularly for class in the laboratory to "get their hands dirty" building their rocket and payloads. During this phase, but prior to the first launch, the contractor must also submit two important CDRL items (Contract Data Requirements List). The first document is the contractor's Management Data Package. It contains a company organizational chart, milestone charts for each payload and subsystem development, and a launch schedule. The contractor is held bound to its published launch schedule; penalties are imposed by the government for launches delayed beyond the advertised launch dates. The second CDRL item is the Launch Procedure Plan (LPP) which is a detailed written plan for conducting the flight tests. It contains personnel tasks, equipment lists, event sequencing, and contingency plans. In an appendix to the LPP, the contractor describes how to calculate the apogee altitude reached by their rocket from elevation readings from ground tracking equipment.

Prior to each launch the contractor must present a Launch Readiness Review (LRR) to the government. The purpose of the LRR is to demonstrate that everything is "GO" for launch. The briefing covers three main areas:

I. Mission Overview.
II. Launch Vehicle/Payload Readiness Status.
III. Launch Preparation.

The primary objective of the first launch is to verify the rocket's recovery system. Only after the recovery system is proven may the contractor attempt to fly its various payloads. The contractor is limited to a maximum of six launches which accomodate the planned payloads and also allows for a contingency launch in the case of "mishap."

During the flight test phase, launches take place at a rate of once or twice a week. Following each launch the contractor must debrief the results of the mission. The briefing covers the planned test objectives, results, launch costs, analysis of anomalies, and justification of incentive awards. At a minimum each launch costs the contractor \$750 (in Astro 433 dollars): \$400 for the expended motor and a fixed \$350 for launch support services. The contractor will also be charged for any flight hardware that is damaged or destroyed (nose cones tend to be big sellers). On the other hand, the contractor has several opportunities to earn incentive awards and bonuses:

(1) The government can award up to \$1500 for full accomplishment of the mission's primary objective (e.g. recovery verification on the first launch). A portion of this maximum can be awarded for partial success -- but the contractor must justify the award requested.

(2) Per the requirements in the SOW, the rocket must maintain a zero roll rate during ascent. Successful demonstration of this capability will net the contractor \$350 per flight.

(3) Prior to each launch the contractor will predict the apogee altitude its rocket will attain. If the apogee prediction is within ±10% of the measured altitude, \$750 will be awarded; if the predicted value is within ±20% of the actual, \$375 will be awarded.

(4) The government may award a bonus of up to \$250 for a well planned, professionally executed launch attempt. Launches earning this bonus will proceed smoothly, have no delay over two minutes due to circumstances within contractor control, and exhibit efficient set up, countdown, and clean up. Conversely, the government may deduct up to \$500 for a sloppy, unprofessional, botched-up launch attempt.

For each launch, the contractor then determines a performance/cost ratio as follows:

$$P/C = (\text{incentives earned}) / (\text{net flight cost})$$

This ratio typically falls in a range from 1 - 3 for most flights. At the end of the flight test program, the contractor calculates its overall performance/cost ratio: the total performance incentives it earned divided by the total flight costs incurred. The contractor can be awarded an additional bonus depending on how cost effective it was (based on its overall performance/cost ratio) during the flight test program.

Communicate Results

To emphasize the importance of being able to clearly communicate results (the last step in the EDP), the contractor is required to summarize its efforts during the semester in a final briefing to the government. The presentation typically follows this format:

I. Performance Objectives
II. Company Organization
III. Baseline Rocket Configuration
IV. Payloads/Subsystems
V. Flight Test Summary
VI. Schedule/Adherence
VII. Costs
VIII. Lessons Learned

In addition to the briefing, the team must also submit a final written product in the form of a Company Notebook. The notebook contains design data for the rocket and payloads, company management information, and a synopsis of the flight test program. These notebooks are saved and kept on file so they can be used as references by students taking the course in future semesters.

Grading

Since Astro 433 is an academic course, the cadets have to be graded in some manner. The basis for their grade is the "money" they earned individually for their payload/subsystem design and the incentives accrued by their team. As a rule, the money earned collectively as a team is added directly to each team member's total. The instructors may, however, alter this normal distribution to reflect unusually good or poor performances by individual team members. Peer evaluations are very helpful in discerning which persons contributed the most (and least) to the team effort. A break-down of the total incentives available is shown below.

Team Design Efforts	$7,000
Individual Design Project	24,000
Company Evaluation (CDRLs, etc)	9,000
Launches	about 15,000
Cost Effectiveness	3,000
TOTAL	about $58,000

The amount of incentives available for award tends to increase each semester - usually keeping pace with the inflation rate.

Concluding Comments

Astro 433 is the "put-it-all-together" course in the Air Force Academy's Astronautics curriculum in which cadets draw on the knowledge and skills they have acquired in their other engineering courses to solve the problem of designing a rocket powered vehicle. The feature of the course that makes Astro 433 unique is the requirement that the cadets have to actually implement their paper designs. The most valuable learning takes place when the cadets have to struggle with hardware to build and test their systems and when they are forced to investigate, analyze, and agonize over their failures. It is through this "experiential learning" that cadets gain a true appreciation for all aspects of the engineering design process.

References

1. Rhoads, H., et al. "Aerospace Vehicle Systems Design Course -- A Primer for the practice of engineering," 1987.

2. Astro 433 Student Handbook, Department of Astronautics, United States Air Force Academy, 1989.