Hypersonic Re-entry Testing

(Technical Paper)

Global Hypersonic Weapon Competition

(STS Paper)

A Thesis Prospectus Submitted to the

Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree
Bachelor of Science, School of Engineering

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Fall, 2022

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Introduction

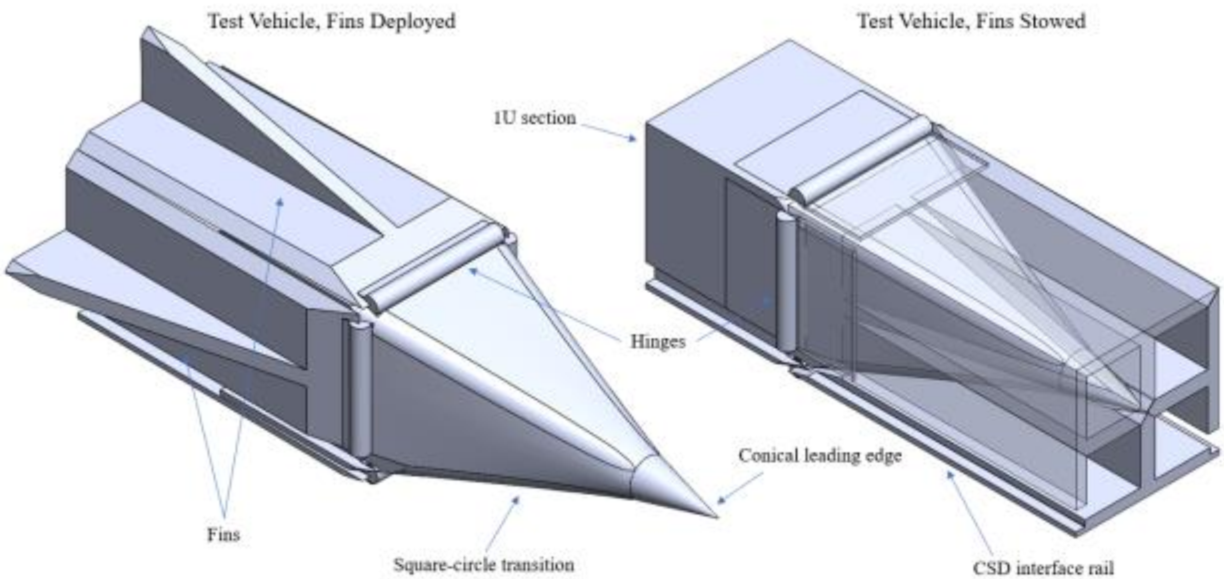
Hypersonic flight experiments are expensive to conduct. The speed at which an air/spacecraft goes will have a significant effect on the behavior of the medium the craft is traveling through. The term hypersonic refers to the projectile's speed in relation to the speed of sound in the environment it is traveling through. A vehicle is considered hypersonic when it reaches a speed five times the speed of sound. Given that most of how we understand the interactions of a flight vehicle with its fluid environment largely rely on experimental data, it is important to create experiments that will evaluate the conditions of hypersonic flight. Due to how expensive hypersonic flight experiments are, the United States has not done sufficient testing to be able to answer global hypersonic weapon competition. Hypersonic research is a large contributor to the Department of Defense's (DOD) spending in the United States. This spending is due to the competition in adversarial countries like Russia and China. Although it is not widely discussed, the United States is behind other countries in hypersonic development. Naturally, to develop said hypersonic weapons and defense systems, the United States must be able to continually experiment in the field of hypersonics. The development of economical ways to understand hypersonic flight can be used to ensure the safety of the citizens of the United States.

Hypersonic Re-entry Testing

To address the expensive nature of hypersonic testing, Chris Goyne of the Mechanical and Aerospace Engineering department and his Spacecraft Design class intend to demonstrate the feasibility of using CubeSats for low-cost, hypersonic flight experiments via natural deorbit and re-entry. The Hypersonic ReEntry Deployable Glider Experiment (HEDGE) is a flight vehicle concept that can be launched as a CubeSat and reconfigure itself as a hypersonic flight vehicle upon re-entry into the atmosphere. The spacecraft will deploy flaps that will reconfigure the cubic shape of the satellite into a dart shape, as shown in Figure 1. The class is split into six functional teams of four to six students that are each in charge of a subsystem of the satellite. The focus of my technical work is on the Attitude Determination and Control System (ADACS) team.

Figure 1

CubeSat Configuration



Note. Depiction of CubeSat Configuration from HEDGE Critical Design Review (Goyne, 2021)

<u>Importance of ADACS and Orbits</u>

ADACS is a system of components used to determine, adjust, and maintain the position of a craft in orbit. The knowledge and control of the craft throughout its flight allows for manipulation of mission parameters, such as launch windows, flight times, orbital maneuvers, sensor orientation, and reentry zones. Attitude can be controlled both passively through components such as spin stabilizers or fins, and actively with parts such as thrusters or magnetic torquers (Caldwell, 2021). The ADACS subsystem will determine what type of attitude control systems best fit our mission's goals, parameters, and budget.

Objectives of HEDGE Project and ADACS

Prior to flight, the objective of the ADACS team is predicting and modeling the expected orbital path and planning for any potential disruptive forces that would alter the position of the craft. Upon separation from the launch vehicle, the objective changes to real time attitude determination and adjustment to attain spacecraft stability. This is done to ensure the vehicle enters the atmosphere at an optimal attitude for velocity optimization, in accordance with the structure's aerodynamic abilities, and successful data collection. In addition, the ADACS team will aim to provide dependable and consistent ADACS information for the remaining subsystem teams to plan and achieve their objectives with appropriate positional data.

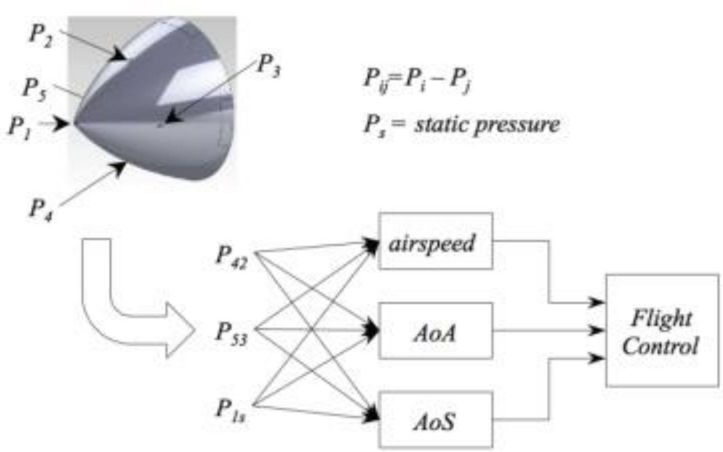
Approach to ADACS and Orbits

The team's approach to ADACS and Orbits is rooted in stability dynamics and pressure sensors. Collaborating with the Structures and Integration functional team, the ADACS team will ensure that the CubeSat's center of pressure is behind its center of gravity. This will require knowledge of the structure and integration of components that will be included in the CubeSat and knowledge of how the stability dynamics will change once the fins are deployed. A main concern for ADACS is tumbling of the CubeSat following ejection from the launch vehicle. To solve this problem, the ADACS team will use previously collected CubeSat data to make predictions about HEDGE's tumbling rate when ejected. With this data, the team will draw conclusions about what technology is needed to mute the tumbling and stabilize the CubeSat.

Potential solutions include a passive attitude control system such as a magnet that would use the Earth's magnetic field to stabilize the vehicle or taking advantage of the aerodynamic stability of the CubeSat once the fins are deployed to stabilize itself as an aircraft would. Alternatively, another solution is an active attitude control system such as reaction wheels that would use the momentum of the wheels spinning on an axis to change the attitude of the spacecraft. Making the decision of which method of stabilization to use will require data collection and testing. Measuring pressure is a main goal for HEDGE's data collection. The ADACS team plans to make use of this goal by implementing a flush air data system (FADS) for attitude determination. FADS is a method of attitude determination commonly used in hypersonic aircraft that "makes use of surface pressure measurements from the nose cap of the vehicle for deriving air data parameters such as angle of attack, angle of sideslip, Mach number, etc." (Shyam Mohan et al., 2018). Figure 1 shows a graphic of how the pressure sensors with FADS would lead to the air data parameter determination.

Figure 2

Flush Air Data Sensing System Diagram



Note. Depiction of FADS System and Process. From Flush Air Data Sensing for Soaring-Capable UAVs (Quindlen & Langelaan, 2013)

Working with the Power, Thermal, and Environment subsystem, our team will determine whether collecting the necessary pressure measurements for the experiment would be possible using a FADS applicable system. Typically, FADS are used at lower altitudes than that of HEDGE at the point of data collection because of the decrease in pressure, which may result in noise having a more significant effect on readings (Shyam Mohan et al., 2018). When the vehicle is in the lower-atmosphere portion of its re-entry, this should not be a concern and FADS should be applicable. During the orbital and upper-atmosphere portions of reentry, HEDGE could use a celestial body sensor, a sun sensor due to weight and size constraints, for attitude determination. A sun sensor could measure the amount of sunlight absorbed on the spacecraft and determine its orientation relative to the sun (Gaebler, n.d.). Another option would be to use magnetometers to measure the magnetic field of the Earth and determine the attitude (*Magnetometer (MAG) | Cassini Orbiter*, n.d.). Based on the requirements for our attitude determination and pressure sensing, the team will choose the number of pressure sensors that can be integrated on the surface of the nose. The number of air parameters which must be derived relates to the number of sensors required (Shyam Mohan et al., 2018). Another consideration will be the tubing and type of sensor chosen, which will be discussed with the Structures and Integration Team and the Power, Thermal, and Environment Team. Finally, our team plans to work with the Communications and Avionics and Software teams to determine how the pressure sensors will collect data and route it to our transmitting device.

Available Resources for ADACS

Our team has several available resources to leverage in accomplishing our goals, including a small operating budget and specialized software. As part of the greater class design team, our ADACS subsystem team has an allotment of funds that could be used to purchase and test attitude determination and control equipment. Access to specialized software like the Ansys Systems Tool Kit (STK) will be important for orbit determination and prediction. To use this software, we will be referring to the STK user guide from Ansys. The user guide provides directions for creating and modeling our spacecraft (*Printed Manual - Comprehensive.Pdf*, n.d.). The advanced space systems prediction capabilities of STK will help us in achieving our goals of predicting and monitoring our spacecraft's orbit.

Anticipated Outcomes for ADACS

The anticipated outcomes of the ADACS functional team are to find a predetermined orbit with a variable launch point via STK software, determine what specific hardware should be used for attitude and orbit determination, and prepare a critical design review (CDR) to submit for proposal. The predetermined orbit should be applied based on which launch vehicle the team uses and where the CubeSat is released in relation to the Earth. Currently, the launch site is undetermined, therefore orbit determination will have to use all known variables and make an estimation of the orbit that can be easily changed and used for a specific launch site. The specific hardware that will be used for the ADACS subsystem will depend on the team's budget, volumetric constraints, and the effectiveness of the hardware in the reentry environment. The CDR of the subsystem will be accomplished when the hardware is determined and tested on the spacecraft.

Global Hypersonic Weapon Competition

The three main reasons hypersonic weapons are being developed all over the world are survivability, speed, and range. A hypersonic weapon is very survivable, which means that it is exceedingly difficult to prevent the weapon from hitting its target. Traditional ballistic missile defenses are not able to detect hypersonic weapons when they are flown at low altitudes, due to the curvature of the Earth. A highly maneuverable weapon moving at hypersonic speeds can evade about any missile defense system currently in use. At such high speeds, it is difficult for missile defenses to detect and react to the weapon. The long range of the hypersonic missiles is inherent to the speed that the weapon achieves. Any vehicle moving at these speeds will be traversing large distances in short amounts of time. All these advantages show that hypersonic weapons can be used as a fast and effective response to conflict from other countries, but development of these weapons is sought out by our foreign adversaries as well.

Foreign Competition

The field of hypersonics is still developing, and there is considerable research and development to be done. The United States has fallen behind on testing of hypersonic weapons as other countries develop their weapons further. There are significant concerns that China's hypersonic glide vehicle technology is more advanced than the Unites States.' In 2019, China launched more ballistic missiles for testing and training than the rest of the world combined (*DOD Releases 2021 Report on Military and Security Developments Involving the People's Repu*, n.d.). The Dong Feng (DF) Series family of missiles are further developed hypersonic missiles that China has advertised. The people's liberation army revealed a new hypersonic missile named the DF-17 at a parade in 2019 (*Hypersonic Weapons Development in China*, *Russia and the United States*, 2022). China continues to develop and test hypersonic missiles at greater rates than any other country in the world.

With current tensions in eastern Europe, it is important the United States has a strategy to deter unwarranted actions of foreign adversaries like Russia. Russia has claimed to develop hypersonic weapons like the Avangard and the Kinzhal (Seldin, n.d.). They have also claimed that the Avangard can house both nuclear and conventional warheads, and that they launched the Kinzhal on a Ukrainian underground warehouse (Ellyatt, n.d.). Russia does not pose as much of a threat as China does, but it is still significant, and should be taken seriously given that it has stated development of its hypersonic weapons are needed to ensure that Russian strategic forces can penetrate future U.S. air and missile defenses. Consequently, as our foreign adversaries continue to develop hypersonic weapons at a fast pace, the United States must respond to these potential threats.

Current ballistic missile defense systems are not able to deter hypersonic weapons from causing damage to the United States. The United States is taking a multi-faceted approach to hypersonic weapons. The Air Force's Air-Launched Rapid Response Weapon program had three tests in 2021 which all failed due to problems during the launch process (Trevithick, 2021). The United States has other hypersonic weapon programs, such as the conventional prompt strike from the navy, the Long-Range Hypersonic Weapon program from the Army, and several others under the Defense Advanced Research Projects Agency (*R45811.Pdf*, n.d.). The United States government has only invested modestly in developing hypersonic defenses, compared with funding for hypersonic striking capability (Losey, 2022). The United States requested $4.7 billion for development of hypersonic weapons, and $225.5 million for hypersonic defense research in 2022 ("Report to Congress on Hypersonic Weapons," 2022). The United States' strategy for hypersonic defense is to integrate ground radar with new satellites to track hypersonic missiles anywhere on the globe. Once the hypersonic weapons have been tracked, the department of defense plans to implement a glide phase interceptor that can effectively intercept a hypersonic missile. These defense systems are not projected to be operational for another eight to ten years (*721348.Pdf*, n.d.).

Conclusion

The HEDGE program will demonstrate how hypersonic testing can be conducted at a lower cost than other government programs. Lower cost hypersonic testing will result in more innovation in the field of hypersonics. The United States must accelerate innovation to be able to answer the dangers that other countries pose and ensure that the country is safe. Since hypersonic missiles may be able to house nuclear warheads, the concept of mutually assured destruction will not hold up when faced with these new dangerous developments in hypersonic weapons. Experimentation in programs like the HEDGE is instrumental to facing these dangers.

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