Supersonic Free-Flight Dynamics Testing in the Stratosphere

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A new technique for obtaining stratospheric free-flight dynamics data for atmospheric entry capsules is described. The Stratospheric Projectile Experiment of Entry Dynamics (SPEED) represents a new approach to characterizing the free-flight dynamics of vehicles in the supersonic and transonic regime of flight. The SPEED test architecture leverages a stratospheric balloon and 3D-printed flight system in a novel two-stage configuration to deliver test articles to supersonic conditions in the atmosphere which achieve dynamic similitude with a full-scale vehicle. Designed to address the limitations of existing test facilities, SPEED captures the complete time evolution of a vehicle's dynamic state while producing a statistically significant number of observed flight trajectories to address the stochastic nature of the wake-driven dynamic stability phenomenon.

SPEED was developed over two years at NASA Ames Research Center. The inaugural flight of the SPEED test platform was conducted in the summer of 2024 where scaled capsules of the Mars Sample Return Earth Entry System and Dragonfly entry vehicle were tested. This paper describes the motivation for a new test architecture, operational constraints and achievable flight test envelopes, the design and development of the SPEED concept, and results from the demonstration flight. Techniques for estimating the dynamic aerodynamic characteristics and atmospheric conditions for each test article individually and as a collective are also discussed.

I. Introduction

Atmospheric entry poses critical challenges in the design and deployment of blunt-body vehicles. The need to survive extreme thermal environments during entry necessitates the use of a blunt body, but this comes at the expense of reducing the dynamic stability of the vehicle. Most blunt entry vehicles exhibit dynamic instabilities in the low-supersonic, transonic, or high-subsonic regime. Such instabilities can pose catastrophic risk to the vehicle and therefore the need to characterize dynamic stability is paramount for all atmospheric entry missions. The underlying phenomena which lead to dynamic instability as well as the impact of design changes on the resulting vehicle behavior are poorly understood. The current state of the art for characterizing vehicle dynamic stability relies on expansive testing across multiple facilities to cover the Mach regime of interest. These test methods suffer from known limitations regarding either the richness of the data that can be collected or the applicability of the test results to the full-scale, free-flight environment that the vehicle will experience. Computational methods offer a promising means to compensate for some of these inadequacies but have not yet been fully validated for use in creating end-to-end data products necessary for mission design. With the shortcomings of current testing facilities affecting mission confidence in the reported values applied to flight simulations and emerging computational methods stuck without an ideal data set to validate against, there is a large and growing need for an innovate new test methodology that provides richer data sets and free-flight environments that closely match a full-scale vehicle.

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Stratospheric free-flight testing offers a new capability to address the gaps in the existing dynamic testing paradigm. By equipping numerous test models with a diverse set of instrumentation and delivering them to an appropriately scaled condition in the atmosphere where the dynamics replicate that of the full-scale vehicle, many of the limitations in the current dynamic testing portfolio can be addressed simultaneously. This capability is being developed under a project at NASA Ames Research Center known as the Stratospheric Projectile Experiment for Entry Dynamics (SPEED). The SPEED project seeks to augment the landscape of atmospheric entry testing by offering a holistic and comprehensive approach to characterizing the dynamic behavior of entry vehicles during various stages of flight.

II. SPEED Architecture Description

SPEED leverages a novel two-stage flight system that employs a stratospheric balloon to facilitate supersonic test conditions and ensure precise data collection. Through the acquisition of real-time data, including accelerations, angular rates, pressures, magnetic fields, and video recordings, the SPEED technology enables a comprehensive and in-depth analysis of capsule behavior throughout the atmospheric entry process. The system is comprised of three primary constituent elements:

1. Drop Platform:

The drop platform provides a mechanical housing to contain the two-stage free-flight vehicles during their ascent beneath a stratospheric balloon. Depending on the lift capacity of the balloon, the drop platform can house numerous flight-systems for a given flight. The maiden flight of SPEED had a mass constraint of 80kg and the drop platform was able to house eight flight systems within that mass allocation. The mechanical parts of the drop platform are made primarily from a light-weight sheet metal construction to maximize the amount of mass dedicated to the experimental payloads. This system also provides thermal regulation by minimizing exposure to convective cooling and radiative heating in the tropopause and stratosphere, respectively. The drop platform system contains its own custom avionics subsystem that provides closed-loop heating to the thermally sensitive components on board and transmits a command from the parent balloon craft to initiate release of the flight-system payloads. The drop platform is covered in a Mylar blanket for thermal protection. Finally, the drop platform includes a drop-release system with "trap doors" which are pre-tensioned to get out of the way of the projectiles and have friction hinges to arrest rebounding. Vectran retention cords and Ni-Chrome hot wire cutters release each flight system. Release of the flight systems from the drop platform initiates the second phase of flight.

2. Projectile

The first SPEED flight included 8 flight systems. The projectile is the first, larger component of each two-stage flight system. The projectile protects and delivers the test article to the desired flight conditions. It is made of:

– Lightweight 3D-printed components for the external structure and aerodynamic shape of the vehicle

– Fins on the aft segment and ballast mass in the forward segment of the structure to maintain static aerodynamic stability

– Retention tabs and friction hinges to retain the test article in the pusher cup until the desired release point

– An on-board custom avionics and sensor system to detect the appropriate environmental conditions and initiate the ejection of the test vehicle

– A custom ejection mechanism that uses springs to eject the test vehicle at the desired moment

3. Test Articles

The test article is the smaller, second stage of each flight system that is housed within the Projectile until the target altitude and Mach number conditions have been met. For applications of the SPEED architecture focusing on the characterization of capsule dynamic stability, the test articles are the entry capsules which have been scaled down using Mach similitude scaling laws. The Test Article collects the desired free-flight data of scientific interest and consists of:

- Lightweight 3D-printed printed structure
- Custom on-board avionics and sensing system to provide power and thermal control, and record vehicle state (accelerations, angular rates, surface pressures, camera video)
- UHF and GPS radio beacons for recovery of the test article after it reaches the ground.

Taken together as a complete system, this architecture enables test capabilities that have previously only been accessible with expensive and stressing launches on dedicated sounding rockets.