A simplified trajectory analysis model for small satellite payload recovery from low Earth orbit

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Abstract

The reentry trajectories of a small mass at low Earth orbit were analyzed with a modified three degree-of-freedom trajectory simulation. An estimate of the stagnation point heating was also made. The mass deployed an inflatable, three-element drag disk decelerator that was modeled as a single circular disk, trailing the payload, normal to the direction of flight. The downrange distance decreased and the time of flight increased with increased decelerator area. The stagnation-point heat transfer rates with a decelerator of sufficiently low ballistic coefficient of 24 Pa was 5–10 percent that of a typical ballistic reentry vehicle with a ballistic coefficient of 4.8 kPa. The study did not find that staged deployment of the decelerator disks provided any aerodynamic advantages, particularly in view of the anticipated complexities involved in deploying such a system. Finally, skip trajectories yielded slightly lower stagnation-point heat transfer than the non-lifting case. However, they may not be advantageous since the increased flight time would expose the decelerator to a longer period of heating, thereby possibly requiring more extensive thermal protection and a potential to damage on-board sensors and instruments.

Keywords: Payload recovery; Reentry; De-orbit; Decelerator

1. Introduction

There is recent interest in using lightweight inflatable decelerators for recovering small payloads, such as LEO satellites, planetary sample return vehicles, sub-orbital rockets and high-altitude scientific balloons, without the weight penalty associated with retrorockets and heat shields or tiles. Additionally, some payloads may require a system to accommodate premature recovery, such as in abortive launches, improper orbital insertions and spacecraft operational failures on orbit.

The increased presence of manned space flight in LEO has also caused increasing concern over hazards posed by space orbital debris. Several concepts have been proposed for reducing the hazards that space orbital debris can pose both in LEO and on the ground. For example, space vehicles in LEO reaching the end of their mission life can be de-orbited or placed in a reduced lifetime orbit to reduce the possibility of an accidental collision. The latter approach can be performed with controlled reentry maneuvers using retro-rockets, which can re-orbit the vehicle to a lower altitude or cause it to reenter and burn up. However, the need to carry additional fuel to accomplish such maneuvers will diminish the space vehicle’s mission. Further, studies have indicated that some of the more massive components of the vehicle may not burn up completely and can reach the Earth’s surface at locations that may be hard to predict.

An alternate approach to spacecraft recovery is proposed. This approach uses an inflatable decelerator system that allows for a precision recovery of the entire vehicle from orbit. The first part of this system involves a large, lightweight inflatable structure that is designed to function as a low mass, area drag brake at high altitude. The second part of this system is a computer guided, parafoil recovery device. The inflatable structure is deployed in LEO to cause an orbital velocity decrease through aerobraking. This decrease in orbital velocity results in a rapid orbital decay of the satellite, which in turn initiates atmospheric reentry. The
inflated structure continues to generate increased drag as the vehicle falls deeper into the atmosphere. A successfully designed drag device will allow the overall vehicle to achieve subsonic velocities well above the optimum parafoil deployment altitude. Once the desired velocity and altitude have been achieved, the inflated structure is released and the autonomous parafoil is deployed for a precision guided final recovery. This may also be the safest way to reduce space orbital debris.

For example, in the recent attempt of the Russian–German Inflatable Reentry and Descent Technology vehicle (launched on February 9, 2000), the shield inflates from a 1 m compact package up to 12–16 m shortly before reentry and then, if it survives reentry, functions as a drag cone to glide the payload back to Earth. The concept of using inflatable decelerators for recovering payloads from space was actually proposed in the late 1940s [16]. In early experiments, nylon parachutes were deployed at altitudes in excess of 180 km. The parachutes were found to partially inflate and then collapse cyclically at high altitude, before becoming fully inflated at low altitude. The outer edge of the parachute canopy was found to be melted due to the high heating rates associated with the high free-fall velocity when the parachute collapsed. To prevent canopy collapse, an inflated ring into artificially inflate the canopy was used successfully [15]. Based on this successful experiment, it was thought that a sufficiently large, high drag device could be used to de-orbit a satellite. A sufficient deceleration high in the atmosphere would significantly reduce aerodynamic heating. However, calculations indicated that the anticipated maximum reentry temperatures far exceed the melting point of nylon. This concept was abandoned in favor of ablative heat shields. All subsequent state-of-the-art recovery systems utilize ablative heat shields and high-speed parachutes, or heat tiles and winged vehicles for final recovery, all of which carry a severe weight penalty.

Only recently have advances in materials technology made the concept of high-altitude payload recovery feasible [5]. Preliminary estimates indicate that an inflatable drag device with a low ballistic coefficient (β = 24 Pa) can operate within the maximum reentry temperatures of recent high-temperature inflatable materials. Such a concept has benefits such as reduced weight compared to ablative heat shields and tiles, lower g-loading on reentry, and the elimination of retro-rockets used for initiating orbital departure. Much of the recent interest stems from aerocapture concepts for entry into planetary atmospheres [6,10,18].

A concept is being developed where a large inflatable decelerator is deployed in LEO to recover a payload from space. This concept consists of three tethered inflatable drag plate decelerator disks that can be deployed in space. The concept is shown schematically in Fig. 1, where the payload has deployed the three disks. Reentry devices that incorporate low ballistic coefficients take advantage of radiation cooling during reentry (unlike contemporary ablation shielding techniques). A radiative material can withstand high total heat loads as long as the maximum heating rate does not exceed the capability of the material. The permissible heating rate is a function of temperature, time at temperature of the material, and the emissivity and heat capacity of the material. Stagnation points on the reentry structure would experience the highest heating rates and this can be reduced by having a large radius of curvature. If a reentry system is light enough (low mass-to-area ratio) that it can be decelerated to relatively low speeds, even if acted on by low drag forces, then the convective heating is minimized by employing shapes with high-pressure drag, namely, blunt bodies with large radii of curvature. Such shapes maximize the amount of heat delivered to the atmosphere and minimize the amount of heat delivered to the drag device during deceleration.

The advantage of deploying a secondary drag body to achieve a low ballistic coefficient configuration is that it shifts a large portion of the total heat load (as much as 80%) away from the primary body. The main payload section (satellite, etc.) is able to make a relatively cool reentry. Little or no redesign would be needed for the payload due to the entire heat load being assumed by the add-on recovery device.

The concept of tethering several drag plates in series is seen as an effective solution to achieving the desired ballistic coefficient. A combination of two or more identical
drag plates in series is additive with respect to drag coefficient when sufficiently spaced to avoid interference [11]. This condition is met under the rarefied conditions of the upper atmosphere. According to Berndt and DeWeese [2], the optimum spacing between drag plates in series is seven disk diameters for continuum flow over a wide range of Mach numbers. This optimum spacing allows the detached flow going around the first disk to reattach prior to encountering the second disk. The second disk can then generate approximately the same maximum drag coefficient of $C_D = 1.2$ that the first disk generates, to create a combined drag coefficient of $C_D \approx 2.4$ for the system (with the same reference area as a single disk). The addition of a third drag plate in series brings the combined total drag coefficient to $C_D \approx 3.6$ for the entire system. The assumption of no interference, while adequate for a simple trajectory analysis, may not be adequate for detailed design of thermal protection or guidance systems [6,7,12,13,17]. One advantage of a tandem disk configuration is that each individual disk can be made small, as opposed to using a single large disk, to meet the ballistic coefficient requirements. The tandem arrangement provides a significant reduction in inflatable material surface area, and thus a proportional reduction in weight, as well as overcoming some packaging and deployment issues.

This paper reports on a preliminary analysis of the trajectory when a small representative payload is de-orbited. Different decelerator concepts were examined. The trajectories were compared with a typical Apollo capsule-type reentry trajectory. Skipping trajectories are also examined as part of this analysis.

2. Method

Trajectories of the reentry vehicle were computed using the Trajectory Simulation and Analysis Program (TSAP) [19]. TSAP solves for point-mass trajectory problems. The code allows the body attitude to be defined and includes the ability to define aerodynamic and propulsion models of arbitrary complexity. During the reentry process, the aerodynamic parameters are first characterized by free molecular flow. The code then allows the simulation to follow a gradual transition to continuum flow as the satellite descends into the denser parts of the atmosphere. Thus, despite being a three degree-of-freedom model, TSAP can reliably simulate trajectories for any vehicle having predictable body dynamics such as aircraft, rocket boosters, spacecraft and reentry vehicles [19]. TSAP enables as many as 99 trajectory segments to be defined since a given mission profile might require a vehicle to assume several configurations and guidance strategies. For this study, TSAP was run on Unix workstations.

As part of the post-processing procedure, aerodynamic drag coefficients were obtained from a simple estimation function of the form:

$$C_D = \frac{Kn + 0.008}{Kn + 0.09} (C_{D, fm} - C_{D, cont}) + C_{D, cont}. \tag{1}$$

In Eq. (1), $C_{D, fm} = 4.0$ and $C_{D, cont} = 1.17$. The convective heat transfer to the stagnation-point along trajectories of the reentry vehicle was calculated using [1,4]

$$\dot{q}_c = \frac{17600 \left( \frac{\rho_\infty}{\rho_{SL}} \right)^{0.5} \left( \frac{U_\infty}{U_{CO}} \right)^{3.15}}{R_{N, eff}}. \tag{2}$$

The effective nose radius for flat disk was estimated using [3]

$$R_{N, eff} = 1.667 D_{flatdisk}. \tag{3}$$

Finally, high temperatures in high-speed atmospheric flight require that the properties behind a shock wave must be obtained using an equilibrium chemically reacting air model instead of a calorically perfect air model. The temperature and density ratios in the shock layer along some trajectory points were obtained from the results of Huber [14] that give the variations of shock temperature and density with velocity and altitude. The equilibrium composition of air at the corresponding temperature and density of the shock layer was computed using the Chemical Equilibrium with Applications (CEA) code [8]. Briefly, this code solves for chemical equilibrium using the minimization of the Gibbs free energy, which is the equivalent of finding the point where the maximum net work obtainable has been extracted from the system.

3. Results

3.1. Single disk

Some selected results are presented here for a 226.8 kg vehicle at 91.4 km altitude, a velocity of 7.31 km/s and a flight-path angle of zero deg (that is, an orbital decay entry) [9]. The calculations were done for a single disk with areas of $S_{ref} = 9.3, 18.6, 27.9, 37.2 \text{ m}^2$. For the present
preliminary analysis, a single disk was used to represent the multiple, tandem disks. The ballistic coefficients for these configurations varied with the trajectory, depending on the values of $C_D$ that varied from free molecular to continuum values, see Eq. (1). Using the continuum value of $C_D = 1.2$, the ballistic coefficients are 200, 100, 66 and 50 Pa. The trajectory of a reentry vehicle with $\beta = 4.8$ kPa was also computed for general comparison. The initial conditions for this vehicle were assumed the same as those of the payload recovery vehicle.

Fig. 2 is a comparison of calculated trajectories for each disk while Fig. 3 shows the velocity–altitude maps and velocity histories. The disk with the largest area had the most aerodynamic drag and, therefore, the most severe initial deceleration (Fig. 3(b)). Most of the deceleration is complete at an altitude of approximately 30 km. The large aerodynamic drag yielded the shortest downrange (Fig. 2(a)) but also the longest deorbit time (Fig. 2(b)). For the ballistic reentry case with a $\beta = 4.8$ kPa, the lack of aerodynamic drag yielded the longest downrange but also the shortest de-orbit time.

The gentler descent with decelerator disks is expected to yield lower convective heat transfer rates as can be seen in Fig. 4. The most severe heating is encountered by the smallest disk. However, for all the four disks, the peak heating is far lower than the ballistic reentry case at about 5–10% of the latter. The peak heating condition occurs early in the trajectory, when the dynamic pressure is still low. Deploying inflatable aerodynamic decelerators in LEO is therefore beneficial from a heat transfer standpoint. However, the early deployment results in the most severe deceleration, as is clearly evident in a plot of the total g-loading (Fig. 5). Moreover, it can be seen that the g-loading for the four disks are of similar magnitude and their peaks are not significantly lower than the ballistic reentry case, being only about 10% lower than the latter. The present results are consistent with the statement in [9] that orbital decay entries yield maximum decelerations of about 8g. The peak loading occurs during a time when the altitude decreases rapidly and the payload enters the lower atmosphere. One can conclude that the peak aerodynamic g-loading is not significantly affected by the use of inflatable decelerators.
3.2. Staged disk deployment

Two cases where the disk area was abruptly increased, or staged, were also examined. The abrupt increase in area was done to simulate the different interactions of the drag plates in free molecular flow (found in LEO), and continuum flow encountered at lower transition altitudes. In free molecular flow, the first disk in the drag plate series is the only one generating any drag effect. However, the drag coefficient for a disk in free molecular flow \( C_D \approx 4.0 \) is found to be much higher than a single disk in continuum flow. Once the drag plate configuration (three disks in series) reaches the continuum flow transition altitude, all three disks generate a combined drag coefficient of \( C_D \approx 3.6 \). The resulting ballistic coefficient remains essentially the same through the free molecular flow region and into the continuum flow region. The area change models ranged from 9.3 to 27.9 m\(^2\) and from 12.4 to 37.2 m\(^2\). The area change was assumed to occur instantly at the transition altitude. The transition altitudes were chosen as 68.6, 76.2, and 83.8 km. Only results for the 9.3 to 27.9 m\(^2\) area change are discussed as results for the latter scheme are qualitatively similar.

The results indicate that the range, flight time or stagnation point heating are not much affected by the staged area increase at transition altitude compared to the constant area case. For example, Fig. 6 indicates a downrange of about 1500 km for the three disk configuration of staged deployment at transition altitude, while the downrange for a disk of constant area of 9.3 m\(^2\) is about 1600 km (Fig. 2(a)). An extremely large \( g \)-loading was obtained, this being an artifact due to the sudden deceleration specified in the simulation model. This result is thus meaningless since, in practice, any staged transition will develop more gently, a situation which is not considered in the present analysis.

3.3. Effect of lift

The possibility of skip pattern trajectories was examined with the introduction of lift forces. Such lift forces may, for example, be developed by tilting the decelerator disks to the incoming flow, or by shaping the disks to obtain a foil shape. The calculations were performed with \( C_L = 0, 0.5, 1.0 \) for a disk of 9.3 m\(^2\). It was thought that lift will result in a gentler trajectory, thus reducing peak heating and \( g \)-loading. Fig. 7 shows that lift significantly increases the downrange of the reentry trajectory. A proportionately larger share of the deceleration occurs at a higher altitude, which also results in a decrease in peak heating and \( g \)-loading compared to the non-lifting case (Figs. 8 and 9). Some other advantages of a lifting entry include an enlarged landing footprint and a wide entry corridor. However, for the present analysis for reentry at extremely low ballistic coefficients, these advantages may be negated by a prolonged exposure to heating, thereby requiring a more elaborate thermal protection system.

4. Conclusions

An exploratory study was made of the reentry trajectories of a 227 kg mass at 91.4 km altitude and a velocity
of 7.31 km/s with a modified three degree-of-freedom technique. The mass and decelerator were modeled as a single circular disk normal to the flight direction. The downrange decreased and the time of flight increased with decelerator area. The stagnation-point heat transfer rates with decelerators were 5 to 10 percent of that of a purely ballistic reentry vehicle having a ballistic coefficient of 4.8 kPa, thus showing the advantage of deploying inflatable aerodynamic decelerators. The study did not find that the staged deployment of the decelerators transitioning from free molecular flow to continuum flow had any adverse results compared to a single large disk of constant area. Finally, skip trajectories yielded slightly lower stagnation-point heat transfer than the non-lifting case. But they may not be advantageous since the longer flight time would expose the decelerator to a longer period of heating.

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References

