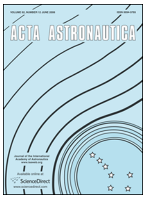
Acta Astronautica 93 (2014) 291–303

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro



Aerothermodynamic and stability analyses of a deployable re-entry capsule

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ARTICLE INFO

Article history:
Received 11 April 2013
Received in revised form
25 June 2013
Accepted 19 July 2013
Available online 26 July 2013

Keywords:
Atmospheric re-entry
Deployable heat shield
Longitudinal stability
Thermal and aerodynamic loads

ABSTRACT

Recent research projects, in the field of atmospheric re-entry technology, are focused on the design of deployable, umbrella-like Thermal Protection Systems (TPSs). These TPSs are made of flexible high temperature resistant fabrics, folded at launch and deployed in space for de-orbit and re-entry operations. In the present paper two possible sphere–cone configurations for the TPS have been investigated from an aerodynamic point of view. The analyzed configurations are characterized by the same reentry mass and maximum diameter, but have different half-cone angles (45° and 60°). The analyses involve both the evaluation of thermal and aerodynamic loads and the assessment of the capsule longitudinal stability. The aerothermodynamic analysis has been performed for the completely deployed heat shield in transitional and continuum regimes, while the longitudinal stability has been analyzed in free molecular, transitional and continuum regimes, also taking into consideration the heat shield deployment sequence at high altitudes.

1. Introduction

In recent years there has been an increasing interest for small space platforms (micro- and nano-satellites), in particular for Earth's environmental protection, prevention of natural disasters and homeland security. Other applications include scientific experiments or technology, space exploration, observation of the universe, astrophysics, biology or physical sciences in microgravity.

Reducing size, mass and power implies a significant reduction of costs and of development time, increasing accessibility to space and sustaining frequent launches. Unfortunately this seems to be in contrast with the increasing problem of space debris. In addition, as a consequence of the miniaturization, these systems require more sophisticated solutions to achieve ambitious scientific and technological goals and to offer the possibility to safely recover the payload and potential data. These are the reasons why novel concepts of deployable aerodynamic decelerators for de-orbit and re-entry purposes have been proposed by the University of Naples, in collaboration with several Italian small, medium and large enterprises [1–4].

These concepts are not completely new in the aerospace community, that already dedicated previous efforts in the study of inflatable or deployable systems for atmospheric re-entry [5–9]. This kind of capsules, in fact, can be easily accommodated in launch vehicles in folded configuration and, when deployed, exhibit a low ballistic coefficient (i.e. the ratio between the capsule mass and its surface, times the drag coefficient). A lower ballistic coefficient implies a larger deceleration in the upper part of the Earth atmosphere, offering as advantage the reduction of the aero-thermal peak loads and, consequently, a much higher reliability of the re-entry phase.

Examples of inflatable systems proposed and already tested are the Inflatable Re-entry and Descent Technology (IRDT) [5] and the Inflatable Re-entry Vehicle Experiment (IRVE) [6]. An inflatable Nanosat De-orbit and Recovery

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http://dx.doi.org/10.1016/j.actaastro.2013.07.030

Nomenclature

a_1, a_2	variable parameters for Eq. (1)
g	gravity acceleration, m/s^2
h	altitude, m
m	satellite mass, kg
mcs	mean collision separation, m
p	pressure, Pa
$\dot{q}$	convective heat flux, W/m^2
r	trajectory radius of curvature, m
r_n	nose-cone radius of curvature, m
s	curvilinear abscissa, m
t	time, s
x	spatial coordinate along the satellite axis, m
y	spatial coordinate perpendicular to the satellite axis, m
B	ballistic parameter, kg/m^2
C_D	drag coefficient
C_{Mz}	longitudinal moment coefficient
Kn_D	overall Knudsen number
M	Mach number
N	number density, m^{-3}
N_c	number of collision cells
N_s	number of simulated molecules
S	reference surface, m^2
T	temperature, K
V	velocity, m/s
α	angle of attack, rad
γ	flight path angle, rad
λ	mean free path, m
ρ	air density, kg/m^3
τ	skin friction, Pa
φ	half-cone angle, rad

Subscripts

cont	continuum regime
f	fluid dynamic
fmf	free molecular flow regime
s	simulated
∞	free stream condition
0	at the stagnation point

System has been specifically designed for CubeSat payloads by Andrews Space [7].

Beside those, different concepts for re-entry systems based on mechanically deployable heat-shields exist. In 1990 a deployable capsule was developed using an umbrella-like heat-shield, made of silicon fabrics and called parashield [8]. A similar satellite called Bremsat was studied in 1996 at the University of Bremen [9].

The solutions considered in the present work consist of a hemispherical rigid nose-cap and a conical deployable umbrella-like TPS made of flexible high temperature resistant fabrics. In the mission scenario, the de-orbit maneuver can be accomplished taking advantage from the aero-brake deployment (i.e. without propulsion systems) and, if required, the re-entry path can be controlled by means of the variable aerodynamic drag resulting from the variable frontal area (i.e. the variable ballistic parameter), in order to correctly target the system in the selected landing area [2]. Two possible architectural configurations for the sphere–cone capsule have been considered. They mainly differ in the half-cone angle (45° and 60°) and for the deployment mechanism. The two configurations will be here labeled as TPS-45 and TPS-60, respectively.

The work is intended to assess the thermal and aerodynamic loads in the most severe conditions along the capsule re-entry path and its longitudinal stability in free molecular, transitional and continuum regimes. The study of the longitudinal stability, in particular, is fundamental to verify that the satellite does not assume a wrong attitude during re-entry, which could compromise the effectiveness of the TPS. A favorable situation can be achieved if the satellite shows longitudinal stability with respect to the nominal equilibrium condition around zero angle of attack and instability for the reverse attitude. In this case, the satellite is aerodynamically self-stabilized and the capsule nose is always aligned with the free stream. For the two analyzed configurations, the longitudinal stability is also investigated considering three intermediate steps during the TPS deployment sequence.

The computations in rarefied flow regimes, i.e. at altitudes higher than 100 km, have been performed by means of the Direct Simulation Monte Carlo (DSMC) method. In continuum flow regime, i.e. at altitudes below 60 km, computational results have been obtained by Computational Fluid Dynamics (CFD). At intermediate altitudes computations have been performed by both DSMC and CFD and thus the comparison between the two methods has been also reported.

The work is organized as follows. In Section 2 the vehicle configurations under investigations are introduced and described. The computing methods and their validation are reported in Section 3. Section 4 deals with the DSMC aerodynamic analysis of the different capsule configurations encountered during the TPS deployment in the range of altitudes between 100 and 150 km. The atmospheric re-entry trajectories are presented in Section 5. The aerothermodynamic analyses performed in transitional and continuum regimes, for significant flight conditions selected along the re-entry trajectories, are reported in Section 6. The main conclusions are summarized in Section 7.

2. System configuration

The capsule consists of a cylindrical structure containing all the subsystems necessary for the on-orbit mission and for the re-entry phase, umbrella-like frameworks, off-the-shelf ceramic fabrics for the conical deployable heat shield and available ceramic materials (e.g. silica, alumina or zirconia) for the rigid hemispherical nose. The necessary subsystems