Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2016-0213

Vol. **23**, No. 4, pp. 1037-1051
April 2018

Monte Carlo Simulation of Spacecraft Reentry Aerothermodynamics and Analysis for Ablating Disintegration

Jie Liang*, Zhihui Li, Xuguo Li and Weibo Shi

Hypervelocity Aerodynamics Institute, China Aerodynamics Research & Development Center, Mianyang 621000, P.R. China.

Communicated by Kun Xu

Received 20 November 2016; Accepted (in revised version) 5 April 2017

Abstract. It is important to have detailed knowledge of large scale spacecraft reentering atmospheric disintegration and main structures melting ablation for an accurate estimate of debris spread area. The direct simulation Monte Carlo (DSMC) method is performed to simulate aerothermodynamic characteristics of Tiangong-1 simplified configuration in rarefied transitional regime during its reentry process. The hybrid Cartesian and surface unstructured triangular meshes as well as adaptive refinement are employed to deal with these complex configuration flows. Internal energy excitations and chemical reactions are considered to compute aero heating precisely. The huge amount of computation difficulties are solved by the DSMC parallel algorithm based on MPI environment. Hypersonic nitrogen flow of Mach 15.6 about a 25/55 deg biconic model is chosen as test cases for validation. The calculated pressure and heating rate distributions have good agreement with the experimental data. Based on the DSMC results of Tiangong-1 shape, the structure stress of solar panels connecting model is analyzed with finite element method. The heat conduction and ablation computations are performed on thin shell structure of spacecraft with one-dimensional model. The height of solar panels broken away from the spacecraft main body is preliminary estimated. The melting ablation of two module structure vehicle is analyzed for different reentering altitudes.

AMS subject classifications: 35Q35, 62P35, 65C05, 74K30, 76K05

Key words: Large scale spacecraft, solar panel, atmospheric reentry, aerothermodynamics, DSMC method, disintegration, melting ablation.

*Corresponding author. *Email addresses:* `liangjie29501@163.com` (J. Liang), `zhli0097@x263.net` (Z. Li), `l_x_g_123@126.com` (X. Li), `38758928@qq.com` (W. Shi)

1 Introduction

Since 1957 and the orbital performance of the Soviet satellite Spoutnik-1, human activity has generated a great number of space debris [1]. More and more space debris reenter the earth's atmosphere randomly due to orbital decay. Most of the random reentry debris has been burnout before reaching the ground because of aerodynamic heating. But large objects (such as launched rocket body, upper stage, large failure satellite or space station) cannot be completely burnt out in the reentry process, the residual debris are scattered in a narrow area along the spacecraft trajectory. If the residual debris scattered in densely populated areas, it would cause great damage on human safety [2]. How to manage this risk has become an issue that is being addressed by the space community [3]. The US Government developed guidelines to limit the hazard from reentering space vehicles [4]. If the casualty expectation of a reentering satellite exceeds one in ten thousand, a controlled deorbit is strongly recommended [5]. A controlled reentry implies that the object can be made to impact any desired location on the earth's surface. Controlled reentries usually target a remote ocean area that is uninhabited. Thus, the risk associated with a successful controlled reentry is essentially zero [6]. Such controlled reentry was performed for both the Compton Gamma Ray Observatory (CGRO) [7] and the Mir space station. Since China's small-scale experimental space station Tiangong-1 was launched in 2011, it has been extended more than three years and will be deorbit and reentering into atmosphere in 2017 in an uncontrolled state. The Tiangong-1 target spacecraft consists of a support module and an experiment module with 7.8m length of solar panels located in each side of support module. This kind of large object may produce great number of fragments during its atmospheric reentry. The debris which are able to survive to the critical aerothermodynamic environment have a potential threat to the ground safety. It is important to have detailed knowledge of solar array panels broken height and main structures melting ablation for an accurate estimate of debris spread area.

There exist several tools for debris reentry analysis and ground risk assessment, including NASA's debris assessment software (DAS) [8] and object reentry survival analysis tool (ORSAT) [9], China's debris reentry and ablation prediction system (DRAPS) [10], ESA's spacecraft atmosphere reentry and aerothermal breakup (SCARAB) [11]. Lips et al. [12] classified the codes into two categories: the object-oriented codes and the spacecraft-oriented codes. Object-oriented codes only analyze individually elements and assume that the spacecraft is broken down into elementary parts at a given altitude (usually between 75 to 85 kilometers). The atmospheric reentry analysis of a whole spacecraft is replaced with the individual analysis of its most critical parts. SCARAB is currently the unique spacecraft-oriented code of modeling the complete spacecraft. The fragmentation or ablation of the spacecraft model depends on the aerothermodynamic environment encountered during the atmospheric reentry.

In present paper, the aerothermodynamic characteristics of a simplified Tiangong-1 spacecraft are computed and analyzed with direct simulation Monte Carlo (DSMC) method during its reentry processes form the altitude 120km to 85km. Based on the