Overview of spacecraft fragmentation testing

Stefano Lopresti[1,a *], Federico Basana[1,b], Lorenzo Olivieri[1,c],
Cinzia Giacomuzzo[1,d], Alessandro Francesconi[2,e]

[1] CISAS “G. Colombo”, University of Padova, Via Venezia 15, 35131 Padova, Pd, Italy

[2] CISAS “G. Colombo” - DII, University of Padova, Via Venezia 15, 35131 Padova, Pd, Italy

[a]stefano.lopresti@unipd.it, [b]federico.basana@phd.unipd.it, [c]lorenzo.olivieri@unipd.it,
[d]cinzia.giacomuzzo@unipd.it, [e]alessandro.francesconi@unipd.it

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Abstract. Spacecraft fragmentation due to collisions with space debris is a major concern for space agencies and commercial entities, since the production of collisional fragments is one of the major sources of space debris. It is in fact believed that, in certain circumstances, the increase of fragmentation events could trigger collisional cascade that makes the future debris environmental not sustainable. Experimental studies have shown that the fragmentation process is highly complex and influenced by various factors, such as the material properties, the velocity and angle of the debris impact and the point of collision (e.g. central, glancing, on spacecraft appendages). In recent years, numerous impact tests have been performed, varying one or more of these parameters to better understand the physics behind these phenomena. In this context some tests have been also performed at the hypervelocity impact facility of the university of Padova. This paper provides an overview of the main experiments performed, the most critical issues observed and proposes some future directions for further research. Moreover, it summarizes the current state of research in spacecraft fragmentation, including the methods and techniques used to simulate debris impacts, the characterization of fragment properties and the analysis of the resulting debris cloud.

Introduction

The increasing presence of space debris poses a significant and escalating threat to the safety of space activities. Collisions with such debris are the primary sources of spacecraft fragmentation, leading to the generation of additional space debris and contributing to an increasingly congested orbital environment [1]. As a result, mitigating space debris has become a top priority for the international space community, necessitating the implementation of effective strategies to reduce the accumulation of space debris and ensure the safety of space operations [2]. Mathematical modelling of this phenomenon is very challenging due to the high velocities involved and the large energies generated during impact. It is therefore essential to perform impact tests that accurately represent the conditions that occur in orbit [3]. In addition, to properly calibrate the models, it is essential to perform parametric tests that allow the influence of the impact geometry (impact angle, velocity, point of impact, etc.) on debris generation to be isolated and studied individually.

To achieve these outcomes, it is crucial to have access to hyper-velocity facilities capable of executing impacts with excellent velocity control.

Hypervelocity impact facility

There are different types of Hypervelocity laboratories that perform impact tests, the most common are the powder-gas guns [4], it is possible to manufacture them in a two-stage light gas configuration that does not involve the use of explosive dust [5].

The conceptual process for both is similar: a piston is accelerated to compress a light gas (usually hydrogen) adiabatically inside a cylinder. The very quick compression leads to a sudden increase in the gas temperature and pressure (about 5000K and 4000Bar peak). When the pressure reaches its peak a valve is opened (usually is a rupture disk that breaks due to high pressure) and the gas is discharged onto a projectile that is fired at high velocity into the target in a vacuum chamber.

The difference in functioning between the two guns is in the way the cylinder is accelerated in the first stage: the light gas gun uses high-pressure gas (e.g., Helium at 120bar) while the second uses gunpowder as a propellant. Both methods are very efficient and it is difficult to compare them, however, from tests, it seems that gunpowder accelerators are able to reach higher velocities while the process with the light-gas guns has higher repeatability, this is because the combustion process is more unstable than unloading a pressurized tank. Moreover, the light gas gun requires significantly less maintenance.

In recent years, research is being directed toward the possibility of manufacturing three-stage accelerators [6]. This achievement would be very interesting because it involves adding a powder stage upstream to existing light gas guns. This could improve the performance of the guns and achieve peak velocities of more than 10 km/s.

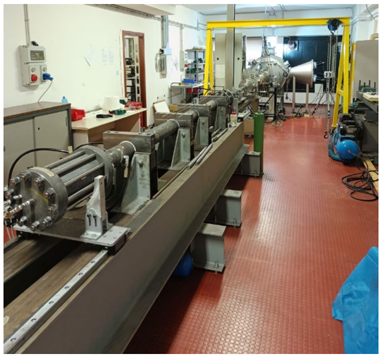

Figure 1: Two stage light gas gun in the hypervelocity facility of the university of Padova.

Fragmentation test

The use of a target with a realistic material distribution is essential to obtain representative results for the physical parameters of the debris. In recent years, there has been increased interest in satellite fragmentation tests to study the response of complex geometries to hypervelocity impacts. The first such impact study was the SOCIT (Satellite Orbital debris Characterization Impact Test) tests series, which was made up of four hypervelocity impacts on representative satellite in space. In particular, in the fourth test, Socit4, the target was a flight ready Navy Transit 1960 era satellite. [7]

An aluminium projectile with a diameter of 4.7cm (150 grammes) fired at a speed of 7km/s was used for the test. The shot was performed on a model of an old generation satellite, therefore the materials are different from those mounted on new-generation spacecraft, for this reason it was decided to carry out a further experimental campaign with more modern targets.

Two hypervelocity tests were conducted in the DebriSat campaign. The first target was a representative upper stage model of a launch vehicle (DebriLV) and the second a 56kg satellite (DebriSat). For both tests, an aluminium cylinder measuring 8.6cm x 9cm was used as the projectile, which was fired at speeds of 6.8 and 6.9km/s, respectively.

DebriLV was composed of 2 pressurised gas tanks of different material and size, the rest of the structure was composed of other materials used in space such as aluminium 6061 and stainless steel [8].

Debrisat is a representative model of a LEO satellite, with a diameter of 60 cm and a height of 50 cm. In addition to using more advanced materials, it was decided to make the satellite 45% more massive than the Socit test. In order to better study the fragmentation of the satellite, each sector of DebriSat was built with different coloured material to better identify its origin [9].

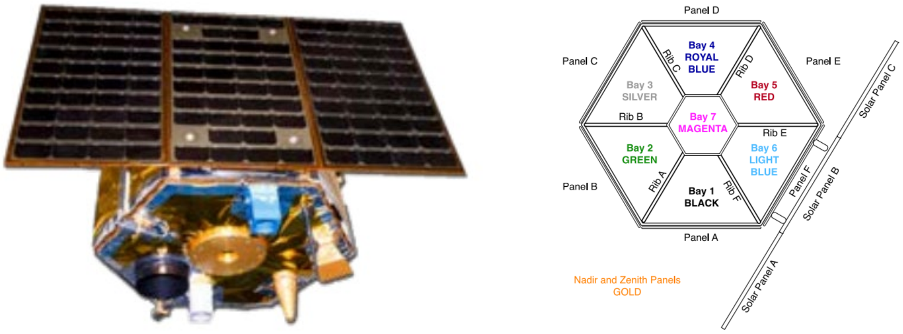

Figure 2: DebriSat photo (left) and schematic representation of the colour subdivision (right).

A rigorous procedure was developed to collect the fragments; the foam panels placed inside the firing chamber were first scanned by X-ray. Once scanned, fragments larger than 2mm were identified, extracted, a characteristic length is measured (the average of the three largest orthogonal dimensions of the fragment) and a unique identification number is assigned. The fragments were then sorted by material, shape and colour and scanned in 2D or 3D [10]. The data were collected and cumulative graphs of mass, shape and size distribution were produced, as well as characteristic length plots with area to mass ratios. This data will be used to improve the modeling of the relationships of these physical characteristics to each other and to calculate more accurate distributions of such parameters.

A team of researchers from CARDC (China Aerodynamics Research and Development Center) carried out a fragmentation test on three cubic aluminium mock-ups of 40x40x40 cm^3 with increasing weights of 7.3, 8.2, and 13.1 kg respectively. Inside these mockups there were a cylindrical central body and representative electronic boxes also made of aluminium, some parts of a printed circuit board were also included. The impact occurred at a speed of approximately 3.5km/s. The fragments were collected and cumulative debris distributions were made in terms of area to mass ratio and cross-sectional area. [11].

A further study was carried out at THIOT Ingénierie and included the fragmentation of a nanosatellite measuring 15x10x10 cm^3. On the satellite were mounted components representative of those used in space such as a 4-cells battery pack, electronic boards, inertia wheels and a solar panel (although it should be noted that they were non-flight acceptable). The projectile used was a 9mm-diameter polycarbonate equilateral cylinder incorporating a second 4mm-diameter aluminium equilateral cylinder fired at approximately 6.7km/s. The size and weight of the fragments were then collected by a six-axis robotic arm that also performed a 3D scan of each analysed fragment [12].

In this context, CISAS also decided to start a test campaign on complex structures. Two tests were performed on a mockup of a Picosatellite of size 50x50x50 mm^3. The first shot was central, with the impact face perpendicular to the projectile (a), while the second test was a glancing impact, performed with the picosatellite inclined at 45° with respect to the projectile direction (b). For these tests, fragments were manually collected, divided by size, weighed and measured to obtain cumulative distributions, characteristic lengths and shape diagrams [13]. The results obtained from the tests were then compared with those predicted by models in the literature (c).

a) b) c)

Figure 3: Experimental setups and characteristic length cumulative distribution.

The glancing impact produced less fragments compared to the other test and also compared to those predicted by the NASA SBM model. However, the inclination of the curves of the experimental and model data have a similar inclination.

Conclusion

Several tests have been performed in recent years to better understand the fragmentation dynamics of a hypervelocity impact. For the development of new models, it is of critical importance to have an increasingly rich and parameterized impact database available for the scientific community. Building new facilities or upgrading existing ones with the objective of reaching higher speeds and find fast and accurate fragment analysis procedures is a key target to achieve this goal.

References

[1] A. Rossi et al, "Modelling the evolution of the space debris population," *Planet Space Sci,* 1988.

[2] J.-R. Ribeiro et al, "Evolution of Policies and Technologies for Space Debris Mitigation Based on Bibliometric and Patent Analyses," *Space Policy,* pp. 40-56, 2018. https://doi.org/10.1016/j.spacepol.2018.03.005

[3] D. McKnight, R. Maher and L. Nag, "Refined algorithms for structural breakup due to hypervelocity impact," *International Journal of Impact Engineering,* pp. 547-558, 1995. https://doi.org/10.1016/0734-743X(95)99879-V

[4] T. J. Ringrose, H. W. Doyle, P. S. Foster and al, "A hypervelocity impact facility optimised for the dynamic study of high pressure shock compression," *Procedia Engineering,* 2017. https://doi.org/10.1016/j.proeng.2017.09.756

[5] A. Angrilli, D. Pavarin, M. De Cecco and A. Francesconi, "Impact facility based upon high frequency two-stage," *Acta Astronautica,* pp. 185 - 189, 2002. https://doi.org/10.1016/S0094-5765(02)00207-2

[6] A. J. Piekutowski and K. L. Poormon, "Development of a three-stage, light-gas gun at the University of Dayton Research Institute," *International Journal of Impact Engineering,* 2006. https://doi.org/10.1016/j.ijimpeng.2006.09.018

[7] J. Liou, J. Opiela, H. Cowardin, T. Huynh, M. Sorge, C. Griffice, P. Sheaffer, N. Fitz-Coy and M. Wilson, "Successful Hypervelocity Impacts of," *NASA Orbital Debris Quarterly News,* pp. 3-5, 2014.

[8] H. Cowardin, J.-C. Liou, P. Anz-Meador, M. Sorge, J. Opiela, N. Fitz-Coy, T. Huynh and P. Krisko, "Characterization of orbital Debris via Hiper-velocity laboratory-based Tests," in *European Conference on Space Debris*, 2017.

[9] M. Rivero, B. Shiotani, M. Carrasquilla, N. Fitz-Coy, J.-C. Liou, M. Sorge, T. Huynh, J. Opiela, P. Krisko and H. Cowardin, "DebriSat fragment Characterization System and Processung Status," in *IAC*, Bremen, Germany, 2018.

[10] M. Rivero, J. Kleespies and K. Patankar, "Characterization of Debris from the DebriSat Hypervelocity Test," in *IAC*, 15.

[11] S.-W. Lan, S. Liu, Y. Li, F.-W. Ke and j. Huang, "Debris area distribution of spacecraft under hypervelocity impact," *Acta Astronautica,* vol. 105, pp. 75-81, 2014. https://doi.org/10.1016/j.actaastro.2014.08.011

[12] H. Abdulhamid, D. Bouat, A. Collè and Al, "On-ground HVI on a nanosatellite. Impact test, fragments recovery and characterization, impact simulations.," in *8th European Conference in Space Debris*, 2021.

[13] L. Olivieri, P. A. Smocovich, C. Giacomuzzo and A. Francesconi, "Characterization of the fragments generated by a Picosatellite impact experiment," *International Journal of Impact Engineering,* vol. 168, 2022. https://doi.org/10.1016/j.ijimpeng.2022.104313