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Demisability and survivability sensitivity to design-for-demise techniques

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ABSTRACT

The paper is concerned with examining the effects that design-for-demise solutions can have not only on the demisability of components, but also on their survivability that is their capability to withstand impacts from space debris. First two models are introduced. A demisability model to predict the behaviour of spacecraft components during the atmospheric re-entry and a survivability model to assess the vulnerability of spacecraft structures against space debris impacts. Two indices that evaluate the level of demisability and survivability are also proposed. The two models are then used to study the sensitivity of the demisability and of the survivability indices as a function of typical design-for-demise options. The demisability and the survivability can in fact be influenced by the same design parameters in a competing fashion that is while the demisability is improved, the survivability is worsened and vice versa. The analysis shows how the design-for-demise solutions influence the demisability and the survivability independently. In addition, the effect that a solution has simultaneously on the two criteria is assessed. Results shows which, among the design-for-demise parameters mostly influence the demisability and the survivability. For such design parameters maps are presented, describing their influence on the demisability and survivability indices. These maps represent a useful tool to quickly assess the level of demisability and survivability that can be expected from a component, when specific design parameters are changed.

1. Introduction

During the past two decades, the attention towards a sustainable exploitation of the space environment has raised steadily. The space around the Earth and beyond has been the theatre of remarkable achievements in the past sixty years but has also suffered from the consequences of the thousands of missions that have flown since then. Decommissioned satellites, spent upper stages, other mission related objects, and fragments generated by collisions and explosions of spacecraft and upper stages pollute the space environment in the form of space debris. Space debris is recognised as a major risk to space missions, in fact, an object of just 1 cm in size can cause the disruption of a satellite, and smaller particles can still have enough energy to produce failures on components critical to the mission success. Recent studies about the evolution of the space environment have shown a continuum increase in the population of space debris [1–4], and the amount of debris is expected to keep growing unless mitigation measures are implemented in the following years. The most effective among these mitigation measures is the limitation of the long-term presence of spacecraft and upper stages in the Low Earth Orbit (LEO) and Geostationary Orbit (GEO) protected regions [5]. This in turn means that a spacecraft has to be removed from its operational orbit after its decommissioning, either by placing it in a graveyard orbit or by allowing it to re-enter into the Earth's atmosphere. For LEO spacecraft, the preferred scenario is to design a disposal by re-entry within 25 years from its decommissioning in order for the mission to comply with the 25-year rule [6]. However, when a spacecraft is to be disposed through re-entry it has also to satisfy the requirement for the limitation of the risk of human casualty on the ground associated to the debris surviving the re-entry. This can be either achieved performing a controlled re-entry, where the spacecraft is guided to impact in the ocean or not populated areas, or through an uncontrolled re-entry, where the vehicle is left to re-enter without any guidance. In the latter case, the surviving mass of the spacecraft has to be low enough to comply with the regulation on the casualty risk expectation that has to be below the threshold of 10^{-4}. Controlled re-entries have a larger impact on the mission performance with respect to uncontrolled ones, as they require a larger amount of fuel to be performed and a higher level of reliability. The spacecraft, in fact, has to carry enough fuel to perform the final

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Abbreviations: DRAMA, Debris Risk Assessment and Mitigation Analysis; MASTER, Meteoroid and Space Debris Terrestrial Environment Reference; MIDAS, MASTER-based Impact Flux and Damage Assessment Software; LMF, Liquid Mass Fraction; PNP, Probability of no-penetration.

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disposal manoeuvre at the end of its operational life. On average between 10% and 40% of the spacecraft initial mass survives re-entry [7]. As a consequence, in order to exploit the advantages of an uncontrolled re-entry strategy in terms of its simplicity and its cost (necessity of new AOCS modes and the possibility to move to a bigger launcher) [7,8] and still meet the casualty risk constraint, design solutions that favours the demisability of the spacecraft and its components can be adopted. This approach is known as design-for-demise, which is the procedure to consider, since the early stages of the mission planning, design options that will allow the demise of the spacecraft in the atmosphere. Among the specific methods employed in designing spacecraft parts to demise, the following can be identified [7,9–11]: selection of the material, use of multiple materials, optimisation of the shape, size, thickness of the component, and changing the component location.

The attention towards design-for-demise has been increasing in the past few years with a growing effort to find solutions to increase the demisability of spacecraft parts and structures. In particular, the European Space Agency, through the Clean Space initiative [12–14] is investing into new demisable solutions for particularly sensitive components such as tanks and reaction wheels. Nonetheless, spacecraft and components designed to demise, still has to survive to the large amount of space debris and micrometeoroids that can penetrate the spacecraft structure and damage components and subsystems. Ensuring the spacecraft reliability against space debris impacts during its operational life is important. It is also necessary to adequately protect the spacecraft after its operational life. Although in this case the main mission of the spacecraft is concluded, it still has to carry out a disposal strategy and comply with the regulations for space debris limitation. In fact, the most critical components inside the satellite still have to be protected in order to avoid possible debris impact induced explosions or break-ups (especially for sensitive components such as tanks and batteries) or compromising the end-of-life disposal strategy. The study here presented focuses on the effect of space debris on LEO spacecraft, neglecting the effects of micrometeoroids, which have lower densities and energies at the altitudes considered in the study.

Design-for-demise solutions can be used to modify the characteristics of spacecraft components; as such, they can also influence the components survivability against the impact from space debris. For instance, can changing the material of a tank to make it demisable compromise its resistance to debris impacts? Can the design of a more demisable configuration increase the vulnerability of the spacecraft to the debris environment?

Considering that the design-for-demise is a relatively new field of study, the aim of this paper is to analyse how a design-for-demise oriented approach can influence other subsystems and other mission requirements. Furthermore, considering that the design requirements connected to the demisability and the ones connected to the survivability (the ability of an object to withstand debris impacts) appears to be conflicting in nature, it is interesting to investigate in which way they can mutually influence each other and to how and to what extent they are influenced by common design choices.

The paper presents a re-entry model used to compute the demisability of a spacecraft its disposal through atmospheric re-entry. In addition, a model developed to assess the survivability of spacecraft components against the impact from space debris during its operational life is presented. A demisability and a survivability indices have also been developed in order to quantify the level of demisability and survivability of a given spacecraft component.

The design parameters affecting both the demisability and the survivability of a component are first identified. The sensitivity of the demisability and the survivability index to the design choices is then analysed. Indeed, the specific re-entry conditions can influence the demisability of an object, in the same way as the operational orbit selection (altitude and inclination) and the mission lifetime can affect the survivability. Finally, the effect of the design-for-demise options on both the demisability and the survivability index is studied using a representative component. Using a spacecraft tank as the reference component, the influence of the design-for-demise options is studied varying each parameter in order to understand to what extent and how they influence the demisability and survivability indices.

2. Re-entry model

The developed re-entry model can be classified under the category of object-oriented codes. It is able to simulate the three degree-of-freedom trajectory for elementary geometrical shapes representative of spacecraft components, i.e., sphere, cylinder, flat plate, box, assuming a predefined random tumbling motion. The ablation is analysed with a lumped mass model; when the melting temperature is reached, the mass is considered to vary as a function of the heat of ablation of the material. All the material properties are temperature independent and have an average value from the ambient temperature up to the melting temperature. Average drag coefficients, shape factors, and correlations needed to describe the aerodynamic and aero-thermodynamic behaviour of the object were taken or derived from the literature. The demise is assessed as the ratio between the residual mass of the object after the re-entry and its initial mass.

The model is the result of a major work of unification of the different sources of information for the heat rate correlations, drag coefficients expressions, and material behaviour sparsely found in the literature. The retrieved information had also to be adapted to the application in exam as it is described in the following paragraphs.

2.1. Re-entry environment

During the descent trajectory, a satellite experiences the effects of the surrounding environment in the form of forces and moments acting on it and influencing its motion. The main sources of external forces are the pressure forces (lift and drag) due to the aerodynamic interaction between the satellite and the Earth's atmosphere, and the gravitational forces generated by the effect of the Earths' gravitational field on the spacecraft. A zonal harmonic gravity model up to degree 4 is adopted in the current version of the software. The radial and tangential acceleration components acting on the satellite due to gravity can be expressed as [15].

$$g_C = \frac{\mu_e}{r}\left\{1 - \frac{3}{2}J_2\left(\frac{R_e}{r}\right)^2\left[3\cos^2\phi - 1\right] - 2J_3\left(\frac{R_e}{r}\right)^3\left[5\cos^3\phi - 3cos\phi\right] - \frac{5}{8}J_4\left(\frac{R_e}{r}\right)^4\left[35\cos^4\phi - 30\cos^2\phi + 3\right]\right\} \tag{1}$$

$$g_\delta = -\frac{3\mu_e}{r^2}\left(\frac{R_e}{r}\right)^2\sin\phi\cos\phi\left\{J_2 + \frac{1}{2}J_3\left(\frac{R_e}{r}\right)\left[5\cos^2\phi - 1\right] + \frac{5}{6}J_4\left(\frac{R_e}{r}\right)^2\left[7\cos^2\phi - 1\right]\right\} \tag{2}$$

where μ_e is the gravitational parameter of the Earth, R_e is the Earth's radius, r is the distance between the centre of the Earth and the satellite, ϕ is the colatitude, and J_k (k = 1, … ,4) are the zonal harmonics coefficients, also known as Jeffery constants.

The atmospheric model implemented in the software is based on the 1976 U.S. Standard Atmosphere [16]. The Earth's atmosphere is divided into two main zones: the lower atmosphere, which extends from the surface to a geometric altitude of 86 km, and the upper atmosphere, which ranges from 86 km up to 1000 km. Each of the two zones is further divided into layers. Within each layer, the temperature is represented with a predefined function of the altitude. Pressure and density are then derived accordingly as functions of the altitude.

The lower atmosphere is divided into seven layers. In each layer, the temperature is assumed to vary linearly with respect to the geopotential