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Survivability to orbital debris of tape tethers for end-of-life spacecraft de-orbiting

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ABSTRACT

Electrodynamic tethers (EDT) represent one of the possible means to de-orbit defunct satellites from Low-Earth-Orbit at end-of-life. However, considering the large area exposed to the space environment and the consequent high number of debris impacts per unit time, a high tether survivability to orbital debris is of primary importance. This paper provides an estimation of the number of fatal impacts per unit time and per unit length on a tape tether, using for the first time an experimental ballistic limit equation that was derived for tapes and accounts for the effects of both the impact velocity and impact angle. It has recently been shown that, tape tethers, as opposite to round wires, are more resistant to space debris impacts. It is shown that considering a tape tether with cross section 45 mm × 50 μm, the number of critical events due to impact with non-trackable debris is always less than 0.01/yr/km, being maximum for orbit inclination of $i = 90°$.

1. Introduction

The use of electrodynamic tethers (EDT) to de-orbit satellites from Low Earth Orbit (LEO) has been studied for more than a decade [1–8]. This technique could be particularly useful for defunct satellite removal as well as post mission disposal of end-of-life spacecraft from crowded orbital regions, thus reducing the chances of *Kessler Cascading* [9].

The core functionality of EDT systems depends on their survivability to Meteoroids and Orbital Debris (M/OD), and a tether can become itself a kind of debris for other operating satellites in case of cut-off due to particle impact. As regards tether survivability, space mission evidences are still conflicting after having a number of tethers deployed in space: in the SEDS-2 experiment (Small Expendable Deployer System) [10], a braided Spectra tether of 0.78 mm diameter and ∼19.7 km length was severed just after 3.7 days in orbit at 350 km altitude and the remaining 7.2 km length at the Delta end appeared to remain intact for the remaining 54 observable days of its orbit life until re-entry on 7 May 1994 [11]; this means there was 1 cut in 460 observable km-days of exposure. Unlike SEDS-2, a 2 mm diameter and 4 km long tether in circular orbit, at an altitude of 1022 km and inclination of 63.4°, survived about 10 years in the TiPS mission (Tether Physics and Survivability Experiment) [12]. It comes out the need of further investigating the resistance of tethers to M/OD impact, and in this framework several investigations have been carried out with reference to round-wire tethers. Such studies show that, depending on single strand or woven configuration of the wire, a particle with size from 1/6 [13] to 1/3 or 1/2 of the tether diameter [14] is enough to cut the rope. Other authors suggest to use 0.25 and 0.33 for this critical value [15,16], while [10] assumed that a tether fails if any part of an adequately large debris passes within 35% of the tether diameter. All these results are based on the assumption that any impact on the wire excavates a crater whose volume depends on the M/OD kinetic energy, and they indeed provide a first estimation of the ballistic limit of a tether. However, they model the impact damage as a crater and hence their application is not rigorously valid for tethers whose cross section is thin, e.g. tapes. Furthermore, the damage dependence from the impact velocity and impact angle is not considered (this latter parameter could be particularly important for tethers with non-axis-symmetric cross section, e.g. tapes).

Recently, tape tethers have been proposed for end-of-life satellite de-orbiting [4,17], and prototypes are currently under development in the framework of the European Commission FP7 BETs project (Bare Electrodynamic Tethers) [18,19]. In this context, to evaluate the survivability of tapes against M/OD impacts and compare it with that of round wires has become a necessity, and a comprehensive analysis on the subject has been initiated by Khan

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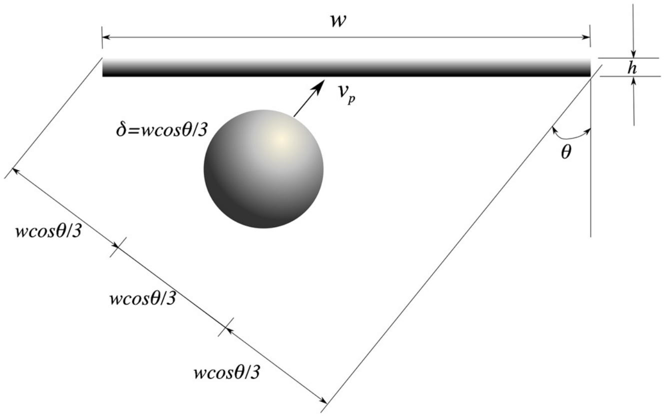

Fig. 1. Tape geometry and orthogonal projection along debris velocity direction.

and Sanmartin [20,21] extending to tapes previous results on the impact survivability of round wires. Assuming that a thin tape is severed by particles exceeding 1/3 of the orthogonal projection of the tape's section along the debris velocity vector (see Fig. 1) pointed out that tapes are less vulnerable to debris impact damage than round wires: for instance, at altitude 800 km and inclination 28.5°, tape tethers survivability was estimated to be about one and a half orders of magnitude higher than a round wire with same mass and length [20] because tape's cross section is reduced as impact obliquity is increased. Taking into account that fatal impact for tapes requires comparatively large and less abundant debris and tapes de-orbit faster, the overall survival probability of a tape during a de-orbit mission could be remarkably higher than an equivalent round wire.

In this framework, this paper provides a further step to enhance the accuracy of the risk predictions for tape tethers, thanks to the use of an experimental Ballistic Limit Equation (BLE) that was developed to account for effects not considered by the 1/3 geometric failure threshold i.e. the damage dependence from impact velocity and impact angle [22]. Such equation predicts the minimum particle diameter δ_m which produces a critical damage (cut-off) at a given speed, v_p, and impact azimuth angle θ, measured in the tape reference frame.

A few different debris-flux models are available based on the data gathered from the measurements over many years. The most prominent models of debris-flux are NASA's ORDEM2000 [23] and ESA's MASTER2009 [24]. Flux values predicted by ORDEM2000 are up to one order of magnitude higher than MASTER2009 in the significant diameter range of a few millimetres [25]. To be conservative, in our analysis we used ORDEM2000 flux data.

The remainder of this paper is organized as follows: Section 2 discusses the approach and the equations used for risk assessment on tapes; Section 3 reports the main calculation results: first, the new BLE used for tapes is compared to the classic, only-geometric, 1/3 failure criterion, then the fatal impact rate (number of severing impacts per unit time and per unit length) for a given thin aluminium tape (45 mm × 50 μm cross section) is presented for a range of LEO altitudes (250–1500 km) and two orbit inclinations (63° and 90°), based on the cumulative debris flux provided by the NASA's Orbital Debris Engineering Model (ORDEM2000) [23]. Conclusions are finally given in Section 4.

2. Debris impact risk on tape tethers

Debris flux is mostly considered to be horizontal on orbital plane. ORDEM2000 assumes orbital debris objects in circular orbits and only considers the horizontal component of the debris velocity. This is justified as the horizontal velocity component is about 6 to 11 km/s while the radial velocity component is generally less than 0.1 km/s [23]. The peculiar shape of tapes (huge length and comparatively smaller width/thickness) and tape being assumed vertical (gravity-gradient) as usual, simplifies the issue of tape moving in apparently horizontal debris environment. In our study, we only consider the orbital debris, avoiding the micrometeoroids which comes from every direction except the earth and thus might needs further consideration of elevation and calculation of surface flux. High survival probability requires low fatal-impact count N_c in a Poisson probability distribution

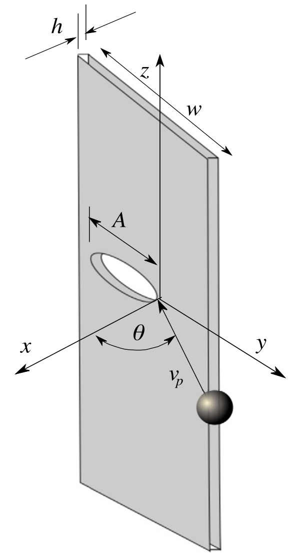

Fig. 2. Impact on tapes: geometry and reference frame.

$$P = e^{-N_c} \approx 1 - N_c \tag{1}$$

where $N_c << 1$. For a tether of length L deployed for a time period of Δt in orbit, one can roughly express the fatal impact rate per unit length, over some debris diameter $\delta > \delta_m$ range written as [20]

$$\frac{N_c}{L\Delta t} \cong \dot{n_c} = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\theta}{\pi/2} I(\theta, v_p), \qquad I(\theta, v_p) = \int_{\delta_m}^{\delta_\infty} \frac{-\mathrm{d}F}{\mathrm{d}\delta}\,\mathrm{d}\delta\, D_{eff} \tag{2}$$

where $F(\delta, v_p)$ is the debris-flux and θ is the impact angle relative to the normal to the tape wide side. The upper bound δ_∞ in the δ-integral can be any large debris size. In our case, we selected $\delta_\infty = 10$ cm, that is the minimum limit of trackable debris for which conjunction analyses and avoidance maneuvers are possible. $D_{eff}(\delta, \theta)$ is the effective tape width calculated according to [27], see equation (3), and takes into account that debris which hit the tape off-center can sever the tether if they remove a critical amount of material A_{crit} from the tape: By definition, A_{crit} is the minimum quantity of material that must be removed to sever the tether, and $\delta_m(\theta, v_p)$ is just enough to produce a damage having size equal to A_{crit}.

$$D_{eff}(\delta, \theta, v_p) = w\cos\theta + \delta - \delta_m(\theta, v_p) \tag{3}$$

where w is the tape width (i.e. the front area per unit length) and $\delta_m(\theta, v_p)$ is the tape ballistic limit, i.e. the minimum debris size that is able to produce a tether critical damage (cut-off) at given impact conditions (angle θ and velocity v_p), measured in the tape reference frame, see Fig. 2 (left). Equation (3) states that a debris having diameter equal to δ and impacting the tether off-center can cause a critical damage provided that its overlapping with the tape is greater or equal to the critical value δ_m.