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Advances in Space Research 56 (2015) 1485–1492

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Optimum sizing of bare-tape tethers for de-orbiting satellites at end of mission

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Received 15 January 2015; received in revised form 8 May 2015; accepted 23 June 2015
Available online 2 July 2015

Abstract

De-orbiting satellites at end of mission would prevent generation of new space debris. A proposed de-orbit technology involves a bare conductive tape-tether, which uses neither propellant nor power supply while generating power for on-board use during de-orbiting. The present work shows how to select tape dimensions for a generic mission so as to satisfy requirements of very small tether-to-satellite mass ratio m_t/M_S and probability N_f of tether cut by small debris, while keeping de-orbit time t_f short and product $t_f \times$ *tether length* low to reduce maneuvers in avoiding collisions with large debris. Design is here discussed for particular missions (initial orbit of 720 km altitude and 63° and 92° inclinations, and 3 disparate M_S values, 37.5, 375, and 3750 kg), proving it scalable. At mid-inclination and a mass-ratio of a few percent, de-orbit time takes about 2 weeks and N_f is a small fraction of 1%, with tape dimensions ranging from 1 to 6 cm, 10 to 54 μm, and 2.8 to 8.6 km. Performance drop from middle to high inclination proved moderate: if allowing for twice as large m_t/M_S, increases are reduced to a factor of 4 in t_f and a slight one in N_f, except for multi-ton satellites, somewhat more requiring because efficient *orbital-motion-limited* electron collection restricts tape-width values, resulting in tape length (slightly) increasing too.

Keywords: Space debris; De-orbit technology; Optimal tether sizing

1. Introduction

Space debris remains a constant menace to operative satellites in Low Earth Orbit (LEO), the risk in setting up the well-known Kessler cascade increasing with time (Kessler and Cour-Palais, 1978). Future satellites should thus incorporate a de-orbit system to be used just at end of mission. Electrodynamic tethers, which are propellant-less and passive systems using Lorentz drag by geomagnetic field **B** on tether current driven by the *motional* field $\mathbf{E_m}$ induced by **B** itself, might effectively remove both future and current non-active satellites (Forward et al., 1998; Van der Heide and Kruijff, 2001; Ahedo and Sanmartin, 2002; Gilchrist et al., 2002; Pardini et al., 2009, 2006). Any de-orbiting system faces two basic requirements: it must (*i*) be light when compared to its satellite, and (*ii*) operate fast to avoid its accidental, catastrophic collision with another large orbiting object, resulting in a myriad of debris pieces. A tether system also faces three particular issues: (*a*) it might be somewhat ineffective at high inclination orbits for which $\mathbf{E_m}$ could prove too weak; (*b*) its geometry (long and thin) make it prone to being cut by abundant tiny debris, leading to a failed operation; and (*c*) its geometry (long) might make it also prone to cut by a big debris.

As regards point (*b*) above, recent results showed that tape tethers have much greater survival probability than round tethers of equal length and mass (Khan and Sanmartin, 2013). Tether geometry has thus a relevant impact on system performance, and tape tethers are advantageous in this respect. Given a mission, i. e. the initial

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http://dx.doi.org/10.1016/j.asr.2015.06.030
0273-1177/

orbital parameters and the mass of the satellite, one might choose tether length L, width w, and thickness h to optimize some figure of merit. Opposite requirements of both a light tether and survivability against debris suggest a design scheme based on the product Π of probability N_f of a cut and tether-to-satellite mass ratio m_t/M_S. Optimal tether design will hinge on both a minimum of the dimensionless function Π and short de-orbiting to reduce manouvers in avoiding big tracked debris.

The present work explicitly shows Π as a functional of tether geometry and orbital parameters, which is derived by combining a fatal-impact rate model introduced in Khan and Sanmartin (2014) and a simple satellite dynamical equation, which assumes a slow de-orbit evolution as sequence of near-circular orbits. Product Π, involving Lorentz drag and space debris impacts, just depends on mission constraints and tether dimensions.

Results from the algorithm highlight important features of bare-tether technology. It is scalable, allowing it to be competitive for a satellite mass range from tens of kilograms to multiple tons, and high inclination effects are moderate. This is illustrated by applying the design algorithm to hypothetical missions for de-orbiting satellites from the Cryosat orbit. Cryosat, an operative Earth-observing satellite following a non-synchronous orbit at 720 km altitude and 92° inclination, was launched in April 2010 to measure polar ice thickness. The algorithm is applied to 37.5, 375, and 3750 kg satellites, and it is also similarly applied for 63° inclination.

In Sections 2 and 3 of the paper the tether survival probability model obtained in Khan and Sanmartin (2014) and the simple deorbit dynamical equation are presented, respectively. These results are combined in Section 4 to obtain both function Π and de-orbit time t_f. Applications of the optimization algorithm are discussed in Section 5 and conclusions are summarized in Section 6.

2. Survival against debris

As already mentioned, results found by Khan and Sanmartin (2013) show that thin-tape conductive tethers have much greater survival probability than round tethers of equal length L and mass m_{ct} of conductive segment. High survival probability over a de-orbit time Δt requires a low fatal-impact final count N_f in a Poisson probability distribution

$$P \approx exp(-N_f) \approx 1 - N_f, \tag{1}$$

where N_f, in case of constant conditions, would be simply related to the fatal-impact count rate, $N_f/L\Delta t = \dot{n}_c$. A value $N_f = 0.05$, say, would mean estimating that 5 among 100 tethers would be cut while de-orbiting.

For the simplest case of a round tether of diameter D, a standard approximation for the fatal impact rate reads

$$\frac{dN_c}{dt} = -\int_{\delta_{m(D)}}^{\delta_\infty} \frac{dF}{d\delta} d\delta \times LD_{eff}(D, \delta), \tag{2}$$

where $F(\delta)$ is the cumulative flux down to debris size δ, at given orbit altitude and inclination, by either ESA's MASTER (Flegel et al., 2009) or NASA's ORDEM (Liou et al., 2002) flux models. In Eq. (2), δ_∞ is a largest debris size relevant as regards cuts, say 1 m, $\delta_m(D)$ is the minimum size that may sever a tether, and $D_{eff} = D + \delta - \delta_c$ is an effective tether diameter for debris collision, which takes into account that debris have macroscopic size and that severing requires a minimum volume overlap of tether and debris trajectories. Energy considerations suggest representative values $\delta_c = \delta_m = D/3$.

For tapes, the fatal impact rate involves an additional integral over impact angle between debris velocity and normal to the wide side of the tape. For a tape-tether of length L, width w, and thickness h, Khan & Sanmartin, making simple approximations, found an analytical representation for either MASTER or ORDEM models

$$dN_c/dt \equiv L\dot{n}_c \approx L\delta^* F^* \times G(n_0, n_1, \delta^*/w, w/h), \tag{3a}$$

$$G \equiv \frac{3n_0 + 2}{\pi(n_0 - 2)} \left(\frac{3\delta^*}{w}\right)^{n_0 - 1} \left(\frac{\pi w}{4h}\right)^{\frac{n_0}{2} - 1} + \frac{n_0 - n_1}{(n_1 - 1)(n_0 - 1)}, \tag{3b}$$

with n_0 and n_1 slopes in a log–log plot of F versus δ for power laws in two ranges $\delta < \delta^*$ and $\delta > \delta^*$, respectively (Khan and Sanmartin, 2014); model accuracy, when compared with numerical computations, proves quite reasonable, maximum deviations reaching upto 12% and 10% for ORDEM and MASTER respectively. The two straight lines in the log–log plot meet at the special point (δ^*, F^*). All four parameters in the model (n_0, n_1, δ^*, F^*) depend on orbit altitude H and inclination. Fig. 1 shows an example of the dependence of these parameters on H at 92° and 63° inclinations, for the MASTER model. In all cases debris diameter δ^* is close to 1 mm. For ORDEM, debris flux might roughly be larger by one order of magnitude.

3. The deorbiting dynamical equation

In an orbiting frame there is a *motional* electric field $\mathbf{E_m} = (\mathbf{v} - \mathbf{v_{pl}}) \wedge \mathbf{B}$ in the highly conductive ambient plasma around, with plasma velocity $\mathbf{v_{pl}}$ near-corrotational and negligible in LEO. A bare tape, its width not sensibly exceeding the electron Debye length, will collect electrons in the *orbital motion limited* regime (Sanmartin and Estes, 1999) over a segment coming out polarized positive. Ions are collected over the complementary segment, at too low rate because of the high m_i/m_e mass ratio; effective current balance requires a plasma contactor, typically a Hollow Cathode (HC), to eject electrons at the cathodic end.

Both tether bias and current I vary along the tether and are determined by solving a boundary value problem (Sanmartin et al., 1993). Current is negligible if $\mathbf{E_m}$ points to the HC, where electrons must be emitted; for a prograde (retrograde) orbit and $\mathbf{u_t}$ the upwards vertical unit-vector,