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Survivability analysis of tape-tether against two concurring impacts with debris

Ricardo García-Pelayo *, Shaker Bayajid Khan, Juan R. Sanmartin

E.T.S. de Ingenieros Aeronáuticos, Universidad Politécnica de Madrid, 28040 Madrid, Spain

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Abstract

It has recently been shown that a thin-tape tether, as opposite to a round one, has a high probability of survival to single impacts by space debris, under a broad range of de-orbit operation conditions. The purpose of the present work is to extend that analysis to survival to multiple impacts by smaller, but more abundant, debris. The method used here consist, essentially, in separating the particles into "large" and "small" ones. The large ones are so rare that the probability of them concurring on the same spot can be neglected. The small ones are a sort of background, and it is shown that the probability of them impinging close enough to a large particle crater to cause malfunction of the tape is negligible. A particular mission is considered, de-orbiting a 3000 kg spacecraft from 800 km altitude at 90° inclination by means of an aluminium tape of dimensions 10,000 m × 0.06 m × (5×10^{-5}) m. It is shown that the probability that this mission survives to multiple impacts is at least 0.978. The application of this method to missions of different parameters is also discussed.

Keywords: Electrodynamic tether; Debris; Probability; Crater; Impact

1. Introduction

A successful operation of an electrodynamic tether system to de-orbit dead satellites necessitates the survival of the tether, which is particularly vulnerable to particle impacts because it is very long and thin. These particles can be Micrometeoroids and Orbital Debris (MMOD). Popular models ORDEM (Liou et al., 2002) and MASTER (Flegel et al., 2009) by NASA and ESA respectively, provide their flux in number of particles per year per square meter, as a function of the particle diameter, δ. Of these two sources we use ORDEM, which is the most conservative of the two (that is, its flux estimation is greater than the one provided by MASTER). The M/OD population responsible for tether failure can roughly be classified in three groups: very large objects (1 m or larger), objects with diameter (δ) ranging from some 10^{-5} m $< \delta <$ 1 m (largely comprised of debris), and finally objects in the size range 10^{-8} m $< \delta < 10^{-5}$ m (largely comprised of micrometeoroids). Particles of diameter smaller than 10^{-5} m are too small to cause significant damage to a tape tether (Hörz, 2012).

A number of tether missions have been carried out in space with survivability issue yet inconclusive. Two major experimental data on the survivability of tethers in space show contrasting results (Cosmo and Lorenzini, 1997; NRO, 1996; Carroll and Oldson, 1995). One of them lasted only a few days while the other one has been orbiting for over 10 years. Conventional wisdom is that something unusual happened to the first one. Even if that is not true these two tethers have lasted an average of five years, which is about an order of magnitude more than the expected time

* Corresponding author.
E-mail addresses: r.garcia-pelayo@upm.es (R. García-Pelayo), bayajid.khan@upm.es (S.B. Khan), juanr.sanmartin@upm.es (J.R. Sanmartin).

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of a typical de-orbiting tether mission (Sanmartín et al., 2015).

From a theoretical point of view it has already been shown that the probability of a tape tether – as opposed to a round tether – to be cut by a single impact is low (Khan and Sanmartín, 2013, 2014). In this article we take the next step, which is to study the probability of a tape tether to be cut by two or more concurring impacts. We show here that this probability is much smaller than the probability of being cut by a single impact. To the best of our knowledge, a quantitative investigation of the survivability of a tether with respect to concurring multiple impacts has never been done before.

In Section 2 the distribution of speeds incident on the tape is derived, which is needed for later developments. In Section 3 the model and its assumptions are explained. The method used in this article divides the particles into "large" and "small" and it will be applied to a tape which is 6 cm wide. In Section 4 the probability that the larger particles do not overlap is computed. In Section 5 it is shown that the probability that the smaller particles cause malfunction of the tape is negligible. In Section 6 the reasons why the assumptions done in this work are conservative are listed, the extension of the computations done here to other cases is discussed and, in particular, the calculations are repeated for a tape which is 2 cm wide.

2. Distribution of speeds incident on the tape

Debris in low earth orbit (LEO) is considered to be mostly in circular orbits (Klinkrad, 2006). For high velocities (>2 km/s), debris velocities in the horizontal plane are highly dominant (Kessler et al., 1989). In fact, debris population model ORDEM2000 (Liou et al., 2002) neglects debris radial velocity altogether and considers it to be in circular orbits.

The debris is not isotropically distributed among all inclinations (see Fig. 1). Its distribution among inclinations mimics the distribution of inclinations among satellites: near polar prograde orbits are the most frequent (Klinkrad, 2006). In this article we take as an example a tape tether in an orbit of 90° inclination and take the total flux incident on it from the ORDEM2000 (Liou et al., 2002) data for 90° inclination.

The distribution of the speed (relative to the tape) of the impinging debris is an essential input of the model presented in this article. In order to find it we need to know how the angle between the orbits of the debris and the tether is distributed. If the inclinations and longitudes of the ascending nodes of the tether and the debris are i_0, i, Ω_0 and Ω (see Fig. 2), respectively, then the angle κ between the orbital planes is given by the following spherical geometry formula:

$$\cos\kappa = \cos i \cos i_0 + \sin i \sin i_0 \cos(\Omega - \Omega_0). \tag{1}$$

This formula simplifies to

$$\cos\kappa = \sin i \cos(\Omega - \Omega_0) \tag{2}$$

for $i_0 = \pi/2$. As stated above, most of the orbits have near polar inclination; to be precise, for 84.3% of them $\sin i > 0.9$ (see Fig. 3), therefore, we may approximate the formula by

$$\cos\kappa \approx \cos(\Omega - \Omega_0), \tag{3}$$

which implies that κ is approximately distributed as $\Omega - \Omega_0$, which is uniformly distributed, because after one turn the orbit's precession changes Ω by an angle which, generically, is not rationally related to 2π.

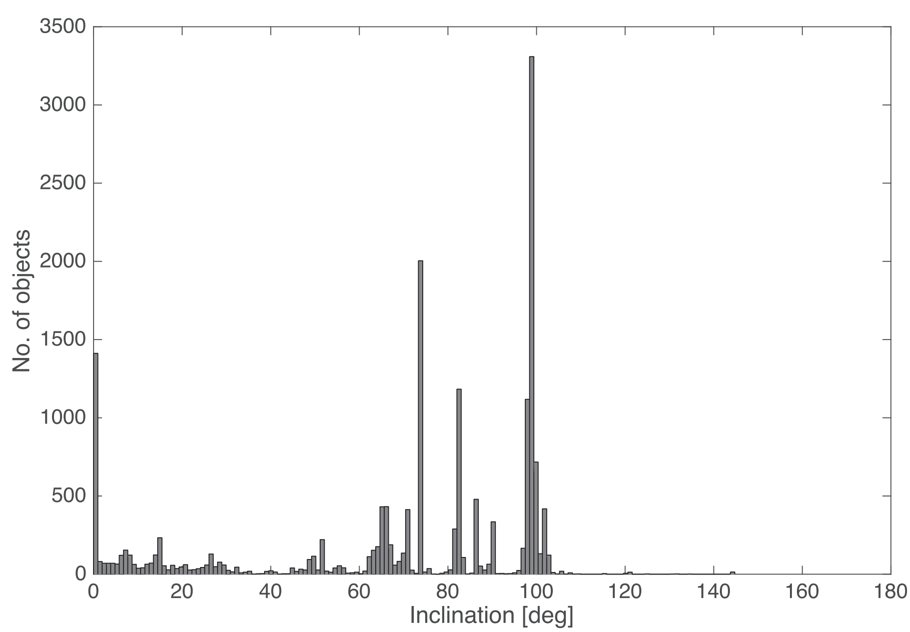

Fig. 1. Distribution of inclinations of the debris. The data are from www.space-track.org.