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The survivability of space tether systems in orbit around the earth☆

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Abstract

The survivability analysis carried out to support the design of a new tether system, being studied in Italy for spacecraft and upper stages end-of-life de-orbiting, is presented. In particular, the problem represented by meteoroids and orbital debris impacts able to cut the tether was addressed, by considering several system configurations in order to find a solution able to meet the baseline mission requirements. In addition, the not negligible collision risk with large intact space objects, and between the tethers themselves, was analysed as well in its implications.

1. Introduction

In Italy, space tethers are being proposed for a growing number of applications, as scientific and technological experiments, space station re-boost and satellite end-of-life de-orbiting. Many efforts were devoted to improve the modelling of tether dynamics and control and the overall system design (deployers, mechanisms, materials, etc.). However, space tethers remain particularly vulnerable to orbital debris and meteoroids impacts, so an important part of any feasibility study must be focused on survivability issues and operational lifetime estimations. In fact, only designs that prove themselves fail safe to a certain confidence level may convince the potential customers of these systems to adopt them for a wide range of promising applications.

The purpose of this paper is to review and address the survivability problem. The detailed analytical and numerical models developed at CNUCE to compute the average impact rate of artificial debris and meteoroids are briefly recalled. Most of the paper, however, is devoted to evaluate the expected operational lifetime, in earth orbit, of a new space tether system, intended to fly in the near future to accomplish the end-of-life de-orbiting of spacecraft and spent upper stages. The compatibility between mission requirements, system design and operational lifetime estimations is analysed and specific suggestions are proposed in the critical cases, in terms of alternative solutions.

Finally, special attention is paid to the implications of having many tether systems in orbit at the same time, causing a possible "disruption" of space operations. Quantitative estimations are provided regarding the tether-to-tether and tether-to-satellite collision probability, taking into account the specific

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geometric properties of long cables as orbital projectiles or targets, when compared to typical space objects.

2. Impact risk

Due to their peculiar structure and geometry, space tethers are particularly vulnerable to small artificial and natural debris impacts, because—at the very high relative velocities characterising the collisions—even a particle smaller than $\frac{1}{2}$ of the tether diameter may cut a single-strand wire. Therefore, a single hit by a very small particle may produce a fatal system failure. Moreover, long tethers significantly increase the collision probability with spent upper stages and spacecraft, and between themselves.

During the last four years, the Italian Space Agency (ASI) and the main national prime contractor for space (Alenia Spazio) funded a few studies, with the relevant participation of the University of Rome "La Sapienza", in order to define the requirements and design the system configuration of an electrodynamic tether for satellite end-of-life de-orbiting [1,2].

In the framework of such research activity, detailed analytical and numerical analyses were carried out at CNUCE, an institute of the Italian National Research Council (CNR), to determine the impact probability of artificial and natural debris and evaluate the average useful lifetime of tethers in earth orbit [3,4]. The meteoroid environment was taken from the International Space Station natural and induced environment definition for design [5]. Concerning the artificial orbital debris, the CNUCE reference population (CODRM-99R) [3,4,6] and the space debris impact risk analysis tool (SDIRAT) [7] were used to determine the impact rate on tethers in circular orbits, as a function of altitude, inclination, debris size and tether diameter. For debris sizes below the lower limit (1 mm) of the CNUCE population, the impact flux was estimated with the NASA's ORDEM96 model [8] (Fig. 1).

A stable tether of length L and diameter d_{T}, deployed along the gravity gradient, presents, for small debris particles with diameter $D \ll d_{\mathrm{T}}$, an effective cross-section $\sim L d_{\mathrm{T}}$. However, for satellites of typical linear dimension $D \gg d_{\mathrm{T}}$, the cross-section becomes $\sim LD$, which may assume very large values, able to compensate the low spatial density of large space objects. In the intermediate debris size range, where $D \sim d_{\mathrm{T}}$, the effective collision cross-section is $\sim L(D + d_{\mathrm{T}})$. Therefore, the differential collision flux does not necessarily decrease when larger and larger space objects are considered, but presents a minimum at a certain intermediate size, which is a function of the tether diameter and debris distribution (see, for example, Fig. 1). For tethers with $d_{\mathrm{T}} > 1$ cm, the risk to be severed does not decrease much by increasing the diameter, because the contribution of large orbital debris to the cutting process begins to dominate [3,4].

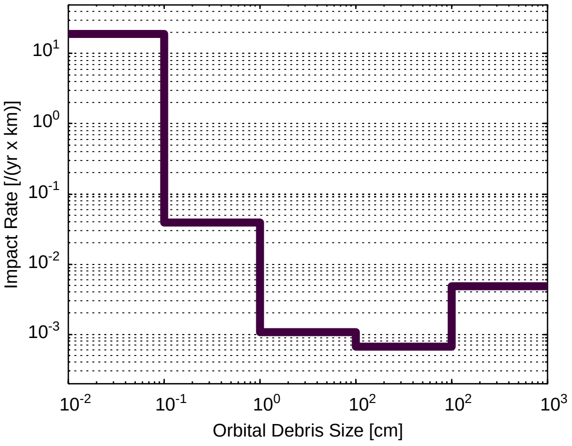

Fig. 1. Differential impact rate as a function of orbital debris size (tether diameter = 1 mm, altitude = 800 km, inclination = 50°).

In order to estimate the probability of severing a cable, it must be recalled that debris quite smaller than the tether diameter may obtain such a result. As an example, an aluminium, single-strand, tether may be cut by a particle $\frac{1}{3}$ of its diameter, while one of woven aluminium could be severed by particles $\frac{1}{2}$ of its diameter [9,10]. An adequately large meteoroid or debris may sever a tether provided its edge passes within 0.20–0.35 d_{T} of the tether's centre of axial symmetry [9]. Figs. 2 and 3 present an example of the expected vulnerability to orbital debris of a 3-mm single-strand wire.

The results obtained confirm that the survivability concern is justified. The danger represented by particles smaller than 1 cm may be overcome by increasing the tether diameter and/or resorting to a creative design. However, the risk of impact with large space