Electro-thermal dynamic simulations and results of a deorbiting tethered system

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Abstract. Deorbiting techniques with small or better no propellant consumption are an important and critical field of space studies for the mitigation of orbital debris. Electrodynamic tethers (EDTs) are of particular interest because they make possible to deorbit space debris by exploiting the Lorentz force that is provided by the current flowing in the tether thanks to the interaction of the system with the Earth's magnetosphere and the ionosphere. This paper focuses on the differences between two software packages built at the University of Padova (FLEX and FLEXSIM) and their results in simulating various deorbiting scenarios. Both FLEXSIM and FLEX simulate the electro-thermal behaviour and the dynamics of an EDT. However, while the first one has the simplifying assumption that the tether is always aligned with the local vertical, the second one considers also the overall system attitude with respect to the radial direction and the tether flexibility. The computational times of these S/W are very different and it is important to understand the scenarios that are more appropriate for their use. Results aim to show the impact of different solar activity (simulations are done at different epochs) and lengths of conductive and non conductive segments of tether, in the range of a few hundreds of meters, on the total re-entry time. As expected, deorbiting is faster for high solar activity and conductive tether length but the performance must be balanced against the dynamics stability. The issue of stability over the deorbiting time is evaluated numerically for specific cases by using FLEX.

Introduction

The interest in the space exploration is increasing day by day because of a steady growth of orbital debris around the Earth. Thus, it's important to find ways to mitigate this growth and electrodynamic tethers (EDTs) represent a possible green and effective solution. Indeed, they don't use the traditional propulsive systems (chemical and electrical), because they can provide good drag forces (i.e., Lorentz forces) by operating in a passive way, that is, exploiting only environmental factors: the ionosphere and the Earth magnetic field.

This work presents briefly how these systems work and then focuses on some analysis of their performances in different deorbiting scenarios. Solar activity influences space environmental characteristics, like the atmospheric and plasma densities, and consequently also the deorbiting time. Consequently, specific simulations are performed to understand how the reentry time and the dynamics of a deorbiting kit based on an EDT change with respect to the solar activity.

Moreover, the effects of the tether length is also analyzed, because it impacts directly the current produced by the tether itself and consequently the Lorentz force generated by the system.

FLEX and FLEXSIM software packages (built by the University of Padova) are used to simulate the different mission scenarios, understand the differences between them and analyze the performance of EDT systems for deorbiting.

Electro-dynamic tether systems

Electrodynamic tether systems are one typology of space tethers [1]; they are based on a conductive tether (or tape) that links two satellites at its ends. If they operate in a passive way, they exploit the current that flows in the tether from the collection of ionospheric electrons on the bare tether anode, that are then re-emitted at the cathode at the opposite end of the tether. The current produces a Lorentz force through the interaction with the geomagnetic field, as follows:

$$\boldsymbol{F}_L = \int_0^L \boldsymbol{I} \times \boldsymbol{B}\, dx \;\approx\; I_{av} L\, (\boldsymbol{u_t} \times \boldsymbol{B}) \qquad (1)$$

In the case of the passive mode, this force is opposite to the orbital velocity of the system, that is, a drag force that progressively decreases the altitude of the spacecraft.

However, electrodynamic tethers can be used in Low Earth Orbits (LEO) to have sizeable performances, because at higher altitude the electron density is too low to generate usable currents.

Software packages

FLEXSIM and FLEX are the chosen software packages to perform simulations. They were both built at the University of Padova for the E.T.PACK initiative [2] to study the electro-thermal dynamic of an EDT deorbiting system. They are different because in FLEXSIM a simplification is assumed: the tether is straight and always aligned with the local vertical and does neither oscillate nor flex, as in a real case. This assumption allows to use FLEXSIM as a first iteration step in the mission evaluation, especially for what concerns the deorbiting time and the computation of the average current in the tether. On the other hand, FLEX simulates the tether dynamics allowing the evaluation of dynamics stability, which is discussed later.

From the modelling point of view, while FLEXSIM considers the tether as a single element, FLEX divides the tether in different segments and computes the dynamics of each one. In FLEXSIM an average current of all the conductive length is considered and used in Eq. 1. In FLEX, instead, an average current and thus a Lorentz force is computed for each segment, leading to a more detailed dynamics of the tether, as stated above.

These two simplifications reduce drastically the computation time of FLEXSIM with respect to FLEX. The codes use a set of subroutines that allows to evaluate the environmental characteristics [3,4,5]. A critical element is the current subroutine, based on [6], that computes the current *I(x)* as a function of the electron density, the motional-electric field and the voltage drop at the cathode.

Numerical Simulations

Several simulations were done to evaluate the performances of the deorbiting tethered system. As just mentioned, the environmental characteristics that determine the current on the tether are influenced by solar activity. Therefore, the same mission is simulated with both FLEX and FLEXSIM at three different epochs, with low, medium and high solar activity (based on the F10.7 index), in order to understand the solar activity impact on the reentry time.

All these simulations were conducted on an EDT with a tape of 500 m (450 m of Aluminum and 50 m of PEEK, the inert segment) and two tip masses of 12 kg. This is the baseline configuration of the In-Orbit Demonstration flight, presently planned for 2025 for E.T.PACK-F. The system is initially on a circular orbit at 600 km height inclined of 51.5°; the mission is considered completed when the system reaches an altitude of 250 km where the atmospheric density is strong enough to reenter the system in a few orbits. As mentioned earlier, the tether length is also investigated as a driving parameter. The investigated scenarios is the same of the previous simulations, but the tether length changes from 400 to 700 m, with a constant percentage of conductive (90%) and non-conductive (10%) tether for all cases. These simulations are done with FLEX, so that, not only the deorbiting time is evaluated, but also the system dynamics, because the variable length leads to a different behavior, allowing for the study of dynamics stability.

Results

Simulations results are now presented, starting from the effects of solar activity. As shown in Table 1 for the case of E.T.PACK-F with 500-m tether, the deorbiting time decreases at higher solar activities, since the electron density increases [7], leading to an improvement of electron collection on the tether and consequently higher currents (Fig. 1) and Lorentz forces.

Table 1 Deorbiting time [days] for different solar activities with FLEXSIM and FLEX

	Low solar activity	Medium solar activity	High solar activity
FLEXSIM [days]	94.152	25.161	19.706
FLEX [days]	88.182	23.267	18.075

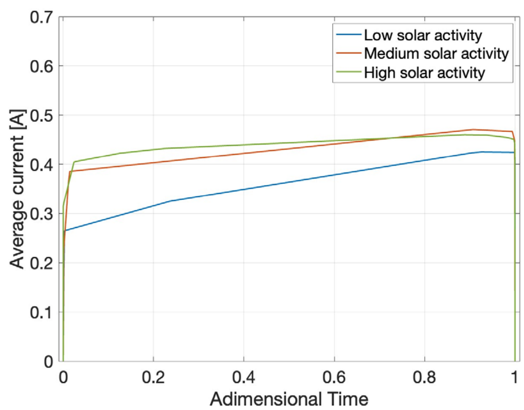

Figure 1 Envelope of current peaks vs time scaled (0 start of mission, 1 end of mission) for low, mean and high solar activity (FLEXSIM)

The differences between FLEXSIM and FLEX in deorbiting times is due to the tether dynamics, which helps the electromotive force (e.m.f.) thanks to the out-of-plane tether dynamics..

Varying the tether lengths at fixed environmental conditions (high solar activity), it is possible to see in Table 2 and Fig. 2, that increasing the length the time of reentry is lower. This is due to the the increase in the e.m.f. that generates higher currents and the increased overall Lorentz force that acts on a longer tether length. However, with a 700 m tether (or longer) instability occurred, the system begins to tumble and could not be controlled. This is due to the increased Lorentz force, and indeed longer tethers require heavier tip masses to be stabilised.

Table 2 Deorbiting time as function of tether length (with high solar flux)

Tether length [m]	400 (360 Al-40 PEEK)	450 (395 Al-45 PEEK)	500 (450 Al-50 PEEK)	600 (540 Al-60 PEEK)	650 (585 Al-65 PEEK)	700 (630 Al-70 PEEK)
Deorbiting time [days]	25.226	21.369	18.075	15.815	13.374	instability

Fig. 3 shows the in and out of plane angles for the configurations with 400 m and 650 m of tether (both stable since the angles never reach the 90 deg). It's possible to see that the blue lines have more peaks than the orange ones, indicating oscillations of longer tether are more persistent, hence these systems are less stable.

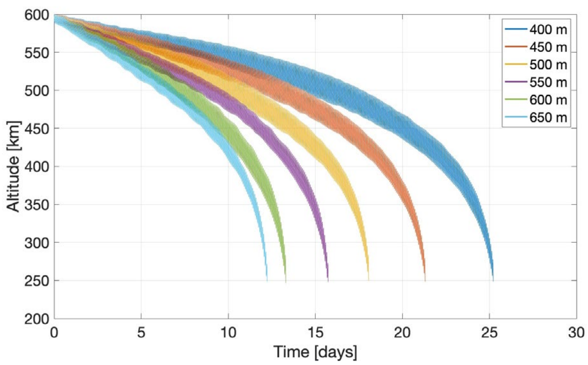

Figure 2 Center of mass altitude vs time as function of tether lengths (FLEX)

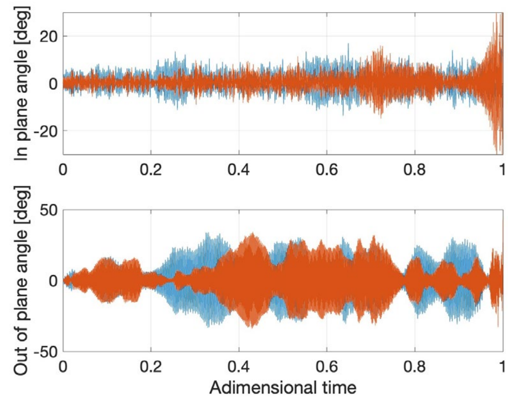

Figure 3 In and out of plane angles for tether length of 400 m (orange) and 650 m (blue)

Conclusions

The focus of this paper is the use of EDT systems for the deorbiting of space debris and the investigation of software packages (FLEX and FLEXSIM) that allow to study EDT performances and their dynamics. From the simulations done for this work, it is possible to confirm that EDTs have better performances at higher solar activities (where they can generate higher Lorentz forces) and with longer tethers. This increased performance must be balanced against the dynamics stability of the system that must be evaluated to assess the feasibility of the mission.

FLEX and FLEXSIM are valid software packages to investigate the performance of EDTs. They are also the starting point to evaluate other applications of tethered system, like EDT operating in active mode for generating thrust to allow a wider spectrum of orbital maneuvers.

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