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ORBITAL DEBRIS MITIGATION THROUGH DEORBITING WITH PASSIVE ELECTRODYNAMIC DRAG

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The increase of orbital debris and the consequent proliferation of smaller objects through fragmentation are driving the need for mitigation strategies. The issue is how to deorbit the satellite with an efficient system that does not impair drastically the propellant budget of the satellite and, consequently, reduces its operating life. We have been investigating, in the framework of a European-Community-funded project, a passive system that makes use of an electrodynamics tether to deorbit a satellite through Lorentz forces. The deorbiting system will be carried by the satellite itself at launch and deployed from the satellite at the end of its life. From that moment onward the system operates passively without requiring any intervention from the satellite itself. The paper summarizes the results of the analysis carried out to show the deorbiting performance of the system starting from different orbital altitudes and inclinations for a reference satellite mass. Results can be easily scaled to other satellite masses. The results have been obtained by using a high-fidelity computer model that uses the latest environmental routines for magnetic field, ionospheric density, atmospheric density and a gravity field model. The tether dynamics is modelled by considering all the main aspects of a real system as the tether flexibility and its temperature-dependent electrical conductivity. Temperature variations are computed by including all the major external and internal input fluxes and the thermal flux emitted from the tether. The results shows that a relatively compact and light system can carry out the complete deorbit of a relatively large satellite in a time ranging from a month to less than a year starting from high LEO with the best performance occurring at low orbital inclinations.

I. INTRODUCTION

The continuous growth of orbital debris constitutes a serious and dangerous risk for space missions around the Earth and, if not mitigated, in the next future it could compromise the launch of new satellites. To help solve this problem and guarantee the safety of key regions of space the Inter-Agency Debris Coordination Committee (IADC) has defined guidelines [1] to follow after the end of life of a satellite in order to mitigate the growth of orbital debris. The guidelines call for spacecraft to be either moved to a "disposal orbit" if in GEO or deorbited within 25 years if in LEO.

For satellites in LEO a very interesting concept for deorbiting is represented by the electrodynamic tethered (EDT) system (see among others Refs. [2-8]). In fact one of the most significant features of these systems is their ability to extract electric power from the plasmasphere of a planet and to produce a sizeable electrodynamic drag. This outstanding characteristic is due to the interaction of the tether with the environment: (1) the motion of the conducting tether with respect to the planet's magnetic field and (2) the presence of the plasma that allows an electrical current to flow in the tether. The system collects electrons from the ionosphere at its anodic end (the conductive tether itself left bare in our case [9]) and emits electrons through a plasma contactor at the cathodic end. The current that circulates in the tether produces the Lorentz drag force through the interaction with the Earth's magnetic field. Power can also be tapped from the tether for running the cathode and other ancillary on-board equipment.

Such a system can carry out a propellantless and relatively quick reentry of satellites in LEO because the Earth's environment is particularly favourable to operating an EDT. In fact the high electron density surrounding the planet at LEO orbits and the magnetic field generate a non-negligible induced potential, which enables the collection of ionospheric electrons at the anodic end of the tether. Consequently, when the electric circuit is closed the interaction between the charged particles and the magnetic field generates a considerable Lorentz force that progressively lowers the orbit of the satellite.

The dynamics of EDTs depends on several factors: gravity gradients forces, electrodynamics interaction and to a lesser extent thermal variations [10]. The Earth's gravitational attraction tends to stabilize the satellite keeping the wire taught and aligned with the local vertical, while perturbations (mainly due to Lorentz force, aerodynamic drag, and solar pressure) change its orbit. Specifically, the electrodynamic force pumps continuously energy into the system attitude motion, increases the libration dynamics, and bends the tether exciting the natural modes of the lateral motion forcing an uncontrolled EDT to go into instability [11]. At last the temperature changes the electric properties of the wire and, consequently, affects the current intensity.

In this paper we presents some results obtained with a new orbital simulator built to investigate in details the dynamical behaviour of an EDT during deorbiting. The code uses a lump-mass approach to model the deflection of the wire to simulate the overall dynamics that is strongly influenced by the tether lateral motion. Parametric analyses have been carried out to study the system performance for different scenarios, in particular by varying the orbital parameters and the tether size. Moreover, a passive control technique has been utilized to provide stability to the system to assure a complete deorbiting.

II. TETHERED SYSTEM MODEL

There are two main models to describe the dynamics of a tethered system: the first is simplified and models the satellite as a rigid dumbbell [12] with an inextensible wire; the second is more accurate and considers the wire as flexible and extensible [13,14]. The dumbbell model is very useful during preliminary studies to obtain quickly information about the system, investigate its performance and identify operative orbital scenarios. On the other hand, the flexible wire model gives a more detailed description of the dynamics, modelling also the lateral bending caused by electrodynamic and aerodynamic forces acting on the tether. The model provides a complete representation of the tether instantaneous shape and includes a number of modes (and modal frequencies) as high as the number of mass lumps for both the lateral and longitudinal dynamics of the tether. For these reasons in the following we will treat the tether as flexible in order to include the lateral dynamics that plays an important role in the stability analysis [15].

II.I Mathematical Model

An effective strategy to model the system dynamics, avoiding mathematical complications, is to discretize the wire as a series of lumped masses connected by massless elastic springs and dampers. The model spatial resolution improves with the number of nodes discretizing the wire, but this increases rapidly the computational time required for the solution. So the number of lumped masses is a trade-off between adequate spatial resolution [16] and the minimization of the integration time without loss of fundamental information about the critical aspects of the system.

The instantaneous state J of each node is defined by seven degree of freedom: the position and velocity vectors and the temperature.

$$J_i = \begin{bmatrix} \mathbf{r} \\ \mathbf{v} \\ T \end{bmatrix} \qquad [1]$$

The motion followed by every lump mass, discretizing the wire, depends on all the forces acting on the system as shown in Eqn. (2). In a detailed analysis the contributions are several because the dynamics is affected by various interactions with the surrounding environment. We can define three main external contributions (gravitational, electrodynamic and aerodynamic forces) and one internal due to the visco-elastic properties of the tether that connects contiguous lumps. The temperature variation of each tether segment depends on all the input and output thermal fluxes affecting it.

$$\dot{J}_i = \begin{bmatrix} \mathbf{v} \\ \frac{1}{m_i}\left(\mathbf{F}_{gr} + \mathbf{F}_{el} + \mathbf{F}_a + \mathbf{Y}\right) \\ \frac{1}{cm_i}\sum Q \end{bmatrix} \qquad [2]$$

In Eqn. (2) c is the specific heat capacity of the wire and m_i the mass of each element used to discretize the tethered system.

Gravitational Force

Each element of tether is subjected to the gravitational attraction. To investigate the gravitational effects accurately we adopt a reference model that includes also the higher harmonics of the gravitational potential, which are mostly important at low altitudes. A 4x4 gravity field model [17] provides enough accuracy for describing the orbital dynamics of the whole system. In summary the gravitational force will have two main contributions: one to model the homogenous Earth gravity attraction and the other representing the uneven mass distribution of Earth. The gravity force can be computed from its potential as follows:

$$\mathbf{F}_g = -\nabla(\frac{\mu m}{r^2}[1-\sum_{n=2}^{\infty}\left(\frac{R_E}{r}\right)^n J_n P_{n0}(\sin\phi) + \sum_{n=2}^{\infty}\sum_{m=1}^{n}\left(\frac{R_E}{r}\right)^n (C_{nm}\cos\lambda m + S_{nm}\sin\lambda m)P_{nm}(\sin\phi)]) \quad [3]$$

Electrodynamic Force

During its orbital motion around the Earth the tether crosses continuously the magnetic field lines generating a motional electric field E_t between the two ends [9]:

$$E_t = (\mathbf{v}_{rel} \times \mathbf{B}) \cdot \hat{\mathbf{u}} \quad [4]$$

where $\boldsymbol{v}_{rel}$ is the satellite relative velocity with respect to the magnetic field, the Earth's magnetic field $\boldsymbol{B}$ is evaluated at the system center of mass and $\boldsymbol{u}$ is the direction of the unit vector joining the satellite with the tip mass at the other end of the tether. When the electric circuit is closed, electrons can be collected from the ionosphere in the anodic portion of the wire and then ejected by the cathode. A conventional current $I(s)$ of positive charges [18] flows along the tether in the direction from the Earth outwards (see Fig. 1), supposing the tether moves eastward on a prograde orbit.

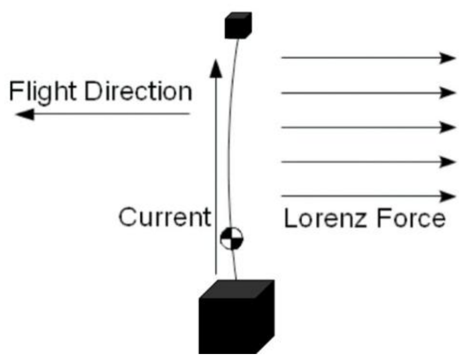

Fig. 1: Electrodynamic force

The current flowing in the EDT interacts with the geomagnetic field generating a Lorentz force working as electromagnetic drag in the opposite direction of the orbital motion (see Fig. 1):

$$\mathbf{F}_{el} = \int_0^L I(s)\hat{\mathbf{u}} \times \mathbf{B} ds \quad [5]$$

Aerodynamic Force

The atmospheric density decreases exponentially versus height above the surface and, consequently, its effects become dominant at low altitudes, causing a rapid decay of the satellite. While the electrodynamic drag prevails at higher altitudes, the aerodynamic drag [17] prevails at very low orbital altitudes. The magnitude of the latter depends strongly on the geometry of the vehicle and its frontal area:

$$\mathbf{F}_a = -\frac{1}{2}\int_A \rho c_D (\mathbf{v}_{rel} \cdot \hat{\mathbf{n}})\mathbf{v}_{rel} dA \quad [6]$$

where $\boldsymbol{n}$ is the normal to the surface element dA.

Internal Force

In a tethered system, two masses orbiting at different heights with a common orbital rate ω_{orb} must be subjected to a tether tension [13] to compensate for the excess or reduction in their velocity. In fact the upper mass runs at higher velocity in order to follow the same orbit, while the lower mass must be orbiting at a slower velocity than the orbital velocity at that altitude.

The motion of the tether relative to the inertial reference system can be described by a set of partial differential equations:

$$\frac{\partial}{\partial s}\mathbf{Y} + \mathbf{f}_{el} + \mathbf{f}_a = \rho_T \frac{d^2}{dt^2}\mathbf{r} \quad [7]$$

where $\boldsymbol{Y}$ is the tether tension, $\mathbf{f}_{el}$ and $\mathbf{f}_a$ the Lorentz and aerodynamic forces per unit length, and s the position along the wire.

The tether tension is important for the response of flexible tethers because it drives the lateral dynamics of the wire. In fact the eigen-frequencies of lateral oscillations (like in a violin string) depends on the tether tension, which is a function of the local deformation of the tether. In a visco-elastic model the tether internal force can be separate in two main contributions: the elastic and damping term:

$$\mathbf{Y} = \mathbf{Y}_{elastic} + \mathbf{Y}_{damp} \quad [8]$$

$$Y_{elastic} = \frac{EA}{l_0}[l - l_0(1+\alpha_T(T - T_0))] \quad [9]$$

$$Y_{damp} = b\dot{l} \quad [10]$$

In the equations above, E is the Young module of the wire, A the cross-sectional area, l and l_0 the instantaneous and initial (i.e., unstretched) length, respectively, of the tether element connecting two lump masses, α_T the thermal variation coefficient, T and T_0 the instantaneous and initial temperature, b the internal viscous coefficient and $\dot{l}$ the length variation rate of the tether element.

Thermal Model

The temperature is important for the dynamical motion because it affects the electrical and mechanical properties of the tether and, consequently, the electrodynamic interaction. Its variation with time depends on several terms [13], defined by the following thermal balance equation:

$$\frac{dT}{dt} = \frac{1}{mc}(Q_{sol} + Q_{al} + Q_e + Q_a + Q_{imp} + Q_{ohm} - Q_{rad}) \qquad [11]$$

In Eqn. (11) Q_{sol}, Q_{al} and Q_e, represent the thermal fluxes due to the Sun, Earth's albedo, the Earth's IR radiation, while Q_a, Q_{imp} and Q_{ohm} are the heating terms related to atmospheric drag, the impact of electrons during collection and the ohmic losses. Finally, Q_{rad} is the only cooling term associated with the radiation emitted by the tether surface into deep space.

The main contributions with typical values of current are due to solar and Earth's albedo fluxes, and, consequently depends on the absorption coefficients of the surface in the visible band. The emitted flux depends on the emissivity coefficient in the infrared band. The maximum temperature of the tether changes as a function of the solar absorbtivity and infrared emissivity coefficients while the minimum temperature (when the satellite is in the shadow) depends only on the view factor of the tether with respect to the planet. When the ratio of visible absorbtivity to infrared emissivity becomes high, the wire absorbs a great amount of solar radiation, but it cannot dissipate enough heat by radiative cooling resulting in high maximum temperatures. High temperatures can be critical because the electric resistance of the tether increases lowering the tether current and the mechanical properties of the wire become weaker.

II.II Electrical Circuit Model

An EDT system consists of a thin conductive wire connected to a satellite. The other termination is generally attached to a tip mass that facilities the deployment of the cable and helps in stabilizing the system through the gravity gradient force. The tether model that we consider is a bare EDT of length L, width w and thickness h, made of conductive material of density ρ and electrical conductivity σ, which is a function of temperature. In this study we will work with relatively short wire, hence it is reasonable to assume that the electron density N_e and the magnetic field B are constant along the tether because their scale heights are too long to cause sizeable variations along the tether length.

The orbiting tethered system cuts continuously the magnetic field lines causing an electric field (e.m.f. or motional electric field) generating an induced potential ΔV_{TOT} between the two extremities [9], which drives the electron collection from the surrounding ionosphere:

$$\Delta V_{TOT} = \int_0^L (\mathbf{v}_{rel} \times \mathbf{B}) \cdot \hat{\mathbf{u}} ds \qquad [12]$$

where $\boldsymbol{v}_{rel}$ is the relative velocity of the tether with respect to the magnetic field lines because the plasma is assumed fixed to the magnetic field and co-rotating with the planet.

The amount of current flowing along the wire depends on several parameters, in particular the plasma density and the geometry of the tether. Moreover, an efficient EDT should be totally or partially bare (see Fig. 2) in order to have a large collecting surface and increase the current level.

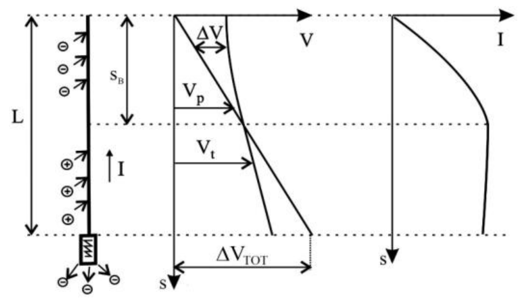

Fig. 2: Electric Current Profile Along The Tether

In such a configuration the electrons are collected in the upper portion of the wire that is positively biased with respect to the plasma, while in the (negatively biased) lower part heavier ions are attracted producing a very small decrease of the electric current. As illustrated in Fig. 2 the electric current profile is non-linear and reaches the maximum at s_B where the potential bias goes to zero. In such a position the potential changes sign to satisfy the drops due to the cathode and, optionally, an electric load on board the satellite. In our simulator the current collection is assumed to take place in the orbital motion limited (OML) regime that is suitable for bare tethers, and the equations governing the dynamics of the charged particles along the wire are [9][18]:

$$\frac{d\Delta V}{ds} = \frac{I}{wh\sigma} - E_t \qquad [13]$$

$$\frac{dI_A}{ds} = \frac{p}{\pi} q_e N_e \sqrt{2\frac{q_e}{m_e}\Delta V} \qquad [14]$$

$$\frac{dI_C}{ds} = \frac{p}{\pi} q_e N_e \sqrt{-2\frac{q_e}{m_i}\Delta V} \qquad [15]$$

In the equations above, I is the electric current (I_A and I_C the current flowing in the anodic and cathodic segments, respectively), ΔV the electric potential difference between the tether and the surrounding plasma, w, h and p the width, thickness and perimeter of the wire [$p = 2\ (w + h)$], q_e the electron charge, m_e the electron mass, m_i the mass of the most abundant ion species.

The component of the motional electric field projected along the wire drives the replenishment of electrons, which also depends on the local electron density. In order to obtain the instantaneous profile of the current and potential bias along the tether the set of differential equations (13-15) must be solved numerically satisfying the closure of the electric circuit:

$$\Delta V_{TOT} = \Delta V_A + \Delta V_{TETHER} + \Delta V_{LOAD} + \Delta V_C \qquad [16]$$

with the following boundary conditions:

$$\begin{array}{ll} I = 0,\ \Delta V = \Delta V_A & s = 0 \\ \Delta V = IZ_{LOAD} + \Delta V_C & s = L \end{array} \qquad [17]$$

where ΔV_A, ΔV_{TETHER}, ΔV_{LOAD} and ΔV_C are the potential drops at the anode, along the tether, the load, and the cathode, respectively. The drop along the tether depends on its electric resistance, hence, on the tether cross-section, length, material electrical properties and temperature.

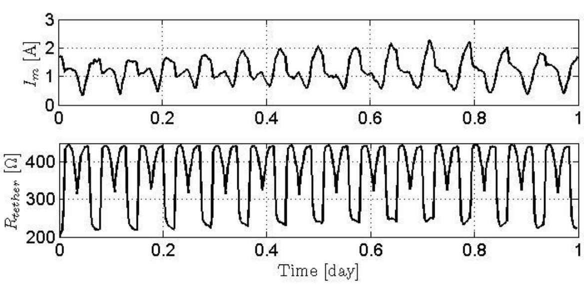

Fig. 3: Mean Electric Current and Electric Resistance of the Tether

Figure 3 shows a typical trend of the average electric current flowing along the tether and its electric resistance, which is a function of temperature, for a short simulation. Both graphs show a strong dependency on the orbital anomaly since the environmental variables change along the orbit. In particular the current has a maximum when the satellite is in the illuminated portion of the orbit, because the solar radiation excites the ionization processes and the electron density increases. The current is minimum when the tether is in the shadow of Earth, because the electron density decreases notably with respect to the sunlit portion of the orbit. As explained previously, the tether temperature, calculated through the thermal balance equation, depends mainly on solar and Earth's fluxes, and ultimately on the α/ε ratio. A low α/ε ratio is desirable for keeping the tether cool throughout the orbit to maintain the electrical resistance sufficiently low and the current level high.

III. LATERAL DYNAMICS

The lateral dynamics of the tether is a very important issue for the whole system because the lateral oscillations can introduce instabilities that a rigid dumbbell model cannot reproduce [11-12]. That is the reason for adopting the flexible model to study the system dynamics during deorbiting. In fact, in-plane and out-of-plane motions are both excited when perturbed by the Lorentz force. The lump-mass model, used here, describes the wire with several nodes that discretize its inertial, electric and thermal properties. A higher number of nodes can improve the description of the motion up to higher frequencies. However, from simulations, we note that the most excited modes of oscillations are the first three, while the higher ones have very low energy. For this reason a model with at least 5 nodes is more than sufficient to describe accurately the dynamics of an EDT satellite, and attain a good trade-off between accuracy and computational efficiency. In fact, the cut-off frequency is sufficiently high to have a rather accurate representation of the first few eigen-frequencies.

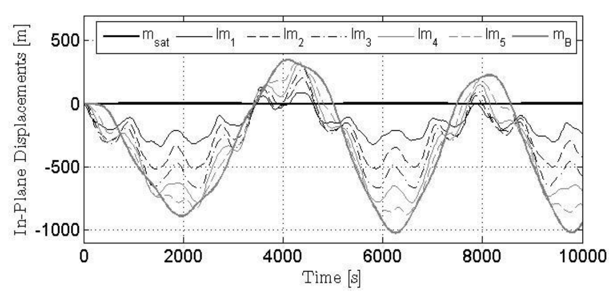

Fig. 4: In-Plane Oscillations

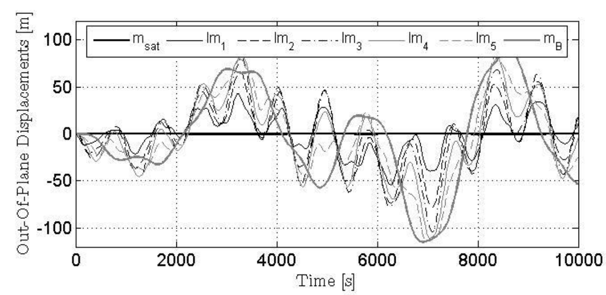

Fig. 5: Out-Of-Plane Oscillations

To show an example of lateral motion we report some results of a brief simulation for an EDT system on a circular equatorial orbit at 1000 km of altitude with a

5-km-long tether. Figures 4-6 depict the motion of each single lump mass with respect to the orbital reference frame in which the *x*-axis is along the radial direction, the *z*-axis perpendicular to the orbital plane and the *y*-axis completes the reference frame. The in-plane and out-of-plane displacements represent the motion along the *y*- and *z*-axis, respectively. The satellite and the tip mass are also treated as lumped masses whose motion is defined by the same set of equations, however, these lumps are not directly affected by the electrodynamic interaction.

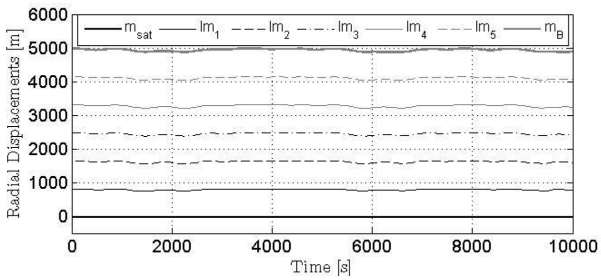

Fig. 6: Radial Oscillations

Another important variable to analyze is the internal visco-elastic tension along the wire (see Fig. 7). Its variations derive from the elastic longitudinal deformation of the tether that depends on the material and geometry of the wire. Note that the tension has a transient response whereby the unforced component is extinguished by the viscous term, and then it reaches a stationary oscillation forced by the gravity gradient term that oscillates around a mean value of about 0.44 N in this particular case. The peaks, more evident in the damping terms, are generated by rapid temperature variations (see Fig. 8) when the satellite passes from sunlight to darkness and vice versa.

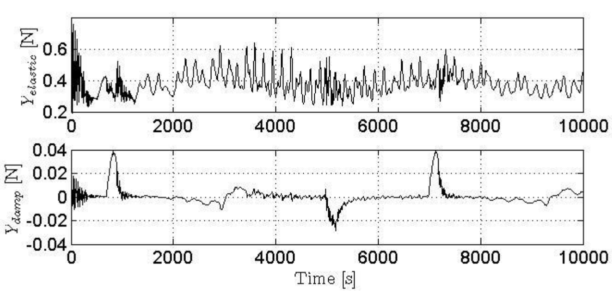

Fig. 7: Elastic and Damping Components of the Mean Tension Force along the Tether

The α/ε ratio chosen for this simulation is equal to 3, and this value limits the maximum temperature of the tether. In a real case the optical coefficients of the wire, in particular in the conductive portion, can have a broad range of values depending on the kind of metal or alloy, and how it has been treated. So ad hoc test are necessary to evaluate accurately the value appropriate for a particular tether material.

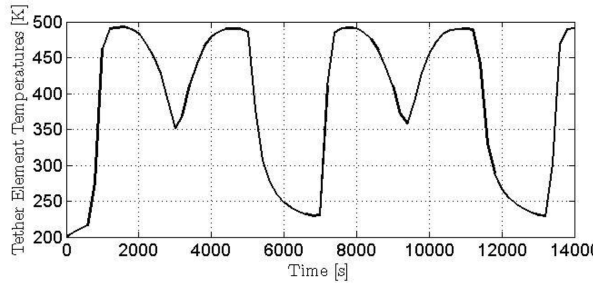

Fig. 8: Temperature Variation of Tether along two Orbits

IV. CONTROL

Without any control, the tethered system goes into a librational instability, hence dedicated techniques are necessary to complete the reentry maneuver. In the past different techniques have been studied for the dumbbell model by several authors based mainly on the control of the current [19-21] or, under very specific assumptions, on the possibility to insert the librational dynamics of the tethered system along a periodic profile [22-24]. In the latter case, the total energy accumulated after a whole oscillation is zero and the in-plane and out-of-plane coupled motion describes a closed loop in phase space. While the current control concept is theoretically easier to implement, the periodic-orbit concept is much more restricted because periodic orbits exist only in ideal cases with periodically repeating environmental conditions

Moreover, when we abandon the simple dumbbell model and adopt the flexible one, the on-off current control of the electric current may not be enough to attain system stability because the oscillations associated with the lateral motion involve more than one mode which are difficult to control all together just by phasing the current.

A new and different approach to controlling the tethered satellite dynamics was investigated by us: instead of monitoring the oscillations and controlling the electric circuit, we adopted a passive damping mechanism. The damper must be placed between the satellite and the electrodynamic tether for dissipating the energy associated with the lateral motion of the ED tether. The damper if properly sized maintains the tethered system stable about the instantaneous equilibrium position determined by the balance of perturbing forces (i.e., mostly electrodynamic) and restoring forces (i.e., gravity gradient). Furthermore, in order to strengthen the stability we added an inert tether in between the ED tether and the tip mass. The combination of the inert tether and the passive damper constitutes what we call a hybrid system that is capable of maintaining stability. In fact, each device by itself would not be sufficient to guarantee an effective control of the tether oscillations under realistic deorbiting conditions but when working together they do allow complete and stable deorbiting under a wide range of orbital conditions. Figure 9 shows a simplified description of the system, where the reader can recognize all the elements mentioned above.

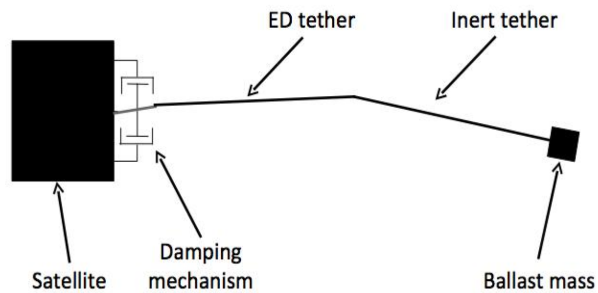

Fig. 9: Schematic of hybrid system

In the literature [25] there are several solutions for passive damping mechanism. They can be divided in two main categories: elastic-damping elements and mechanical dampers. Viscous dampers are based on the relative motion between two elements. The damping force is proportional to the velocity of relative sliding between the surfaces by the viscous coefficient. The strategy proposed in this work uses a rigid "fishing rod" connecting the wire with the satellite. The rod has two degrees of freedom with respect to the satellite and it can rotate, through hinges, about two axes. We neglect the torsional rotation about the longitudinal axis of the tether because it is irrelevant for our aim. In conclusion, the friction in the hinges dissipates a small amount of energy at every tether oscillation and keeps them bounded throughout deorbiting.

V. NUMERICAL RESULTS

In this last part we report numerical results obtained with our simulator for specific cases. Parametric simulations have been run in order to show the capabilities of EDT system to deorbit a satellite. Specifically, the results show the complete reentry from an altitude of 1000 km for various orbital inclinations. In Figure 10, we varied the orbital inclination from 0° to 75° considering several configuration of the tape/wire: two different conductive lengths (3 and 5 km) and width (1 and 2 cm) while the tape thickness is equal to 50 μm. A 500-kg mass was assumed for the satellite and a conservative 20 kg for the tip mass. The tip mass is also important for stability because it helps maintaining the center of mass of the whole system sufficiently close to the electrodynamic center of pressure. For each configuration we assumed an inert tether length equal to the electrodynamic portion in order to double the gravity gradient force and quadruple the torque.

At low inclinations all the configurations work very well and provide fast reentries for both short and long tethered systems: for the shorter 3-km-long wire the deorbiting time is approximately two months and half. As expected, at high inclination the decay time becomes longer for short tethers but it continues to be rather short for the 5-km-long wires. For example at 75° inclination, with a 3-km-long and 1-cm-wide tape the deorbiting takes approximately 170 days to complete, and with a 5-km-long and 2-cm-wide tape it takes about 70 days.

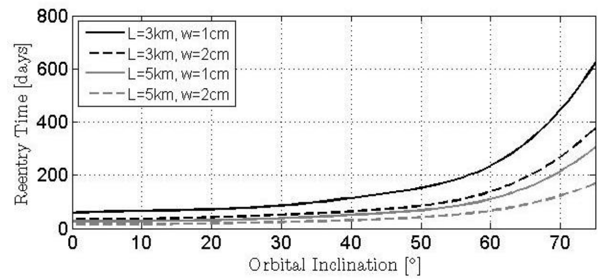

Fig. 10: Reentry Time for Different Configurations of Tether Size

Another interesting aspect to investigate is how the reentry time changes varying the initial orbital altitude. In fact, the relation is non-linear since performance depends on the electron density of the ionosphere, which has a peak at low altitudes (300-400 km), and then decreases with increasing altitude. Figures 11 and 12 clarify this trend: at low altitudes the reentry is very fast while, for high LEO, the deorbiting takes longer, yet still comparatively fast, because the electron population decreases with altitude.

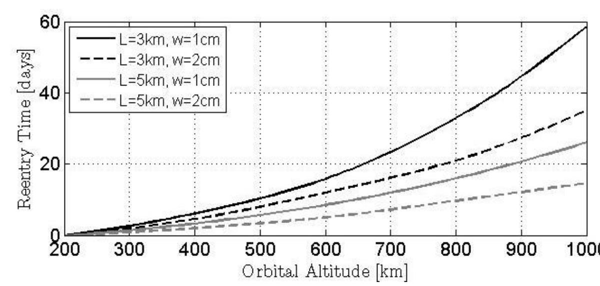

Fig. 11: Reentry Time Required as a Function of Altitude – Orbital Inclination 0°

The main advantage of an EDT system is that it is a propellantless device and so, even if the deorbit starts from high altitudes, the mass of the system does not change. The figures show the time required to complete the manoeuvre, that indeed is longer than by using chemical thrusters but, requiring only a few months, is much smaller than the 25 year time indicated in the guidelines.

Electrodynamic systems are a long way ahead in terms of performance than any neutral drag augmentation devices that are only effective at very low altitudes. Moreover, the electrodynamic system saves fuel when compared to thrusting systems and increasingly so for satellites that are heavy and operating in high LEO. EDT systems are competitive on the basis of mass savings, when compared to chemical thrusters, for deorbiting satellites operating between 700-1500 km of altitude, while the neutral drag augmentation devices are ineffectual in that altitude range. Moreover, the mass savings increases as a function of altitude and spacecraft mass, while the time for reentry is always much shorter than the duration specified in the guidelines. The propellantless characteristic and the ability to produce sizeable Lorentz forces make these devices very interesting for deorbiting spacecraft at the end of life.

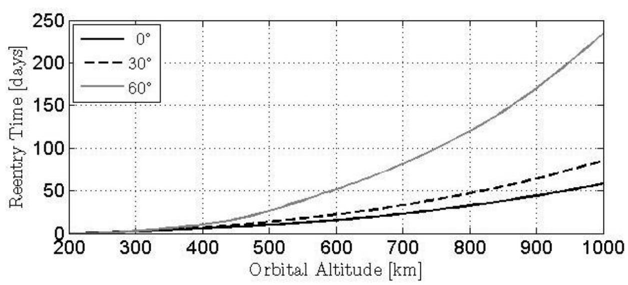

Fig. 12: Reentry Time Required as a Function of Altitude – Length = 3 km, Width = 1 cm

VI. CONCLUSION

A new lump-mass model has been developed and utilized to simulate the dynamics, thermodynamics and electrodynamics of a bare tethered satellite operating in Earth's orbit. The simulator utilizes up-to-date environmental routines for magnetic field, ionosphere, atmosphere and gravity field, and it has been used to simulate the full dynamics of a tethered system during deorbiting of satellites at end of life. Reentry times are rather short when using high performance, few-kilometer-long, bare tethers that can collect efficiently electrons from the environment to flow intense electric currents along the wire. However, this occurs to the detriment of the attitude stability of the system. In order to guarantee stability under a wide range of conditions, a hybrid tether system has been studied and is presented in this paper: a passive damping mechanism at the satellite attachment point was combined with an inert tether placed between the conductive wire/tape and the tip mass. Such a configuration enables the passive stabilization of the system, maintaining the tether as close as possible to its equilibrium position during the entire deorbiting manoeuvre. The parametric results, obtained through comprehensive simulations, show clearly the capabilities of electrodynamic tether systems and highlight how such propellantless technology can be competitive for deorbiting manoeuvres.

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