Electrodynamic tethers in space: dynamical issues, solutions and performance

Enrico Lorenzini[1] and Riccardo Mantellato[2]

University of Padova, Department of Industrial Engineering and
CISAS "G. Colombo" Research Center

Abstract

Electrodynamic tethers are a promising new technology for a variety of applications ranging from deorbiting of spent satellites and upper stages in low Earth orbits to propellantless propulsion around any planet (inclusive Earth) with a magnetic field and a plasmasphere. However, the continuous application of electrodynamic forces/torques over a relatively long period of time raises dynamical issues related to the tether attitude dynamics that need to be solved for achieving long-term dynamical stability. The paper addresses firstly the fundamentals of the dynamical motion forced by the electrodynamic forces/torques and secondly reviews the techniques used to control the motion generated by those forces/torques. The paper also presents the techniques that were used successfully in simulation to control the dynamics of a tethered system designed for deorbiting spent satellites in low Earth orbits and shows its deorbiting performance at all orbital inclinations.

1. Introduction

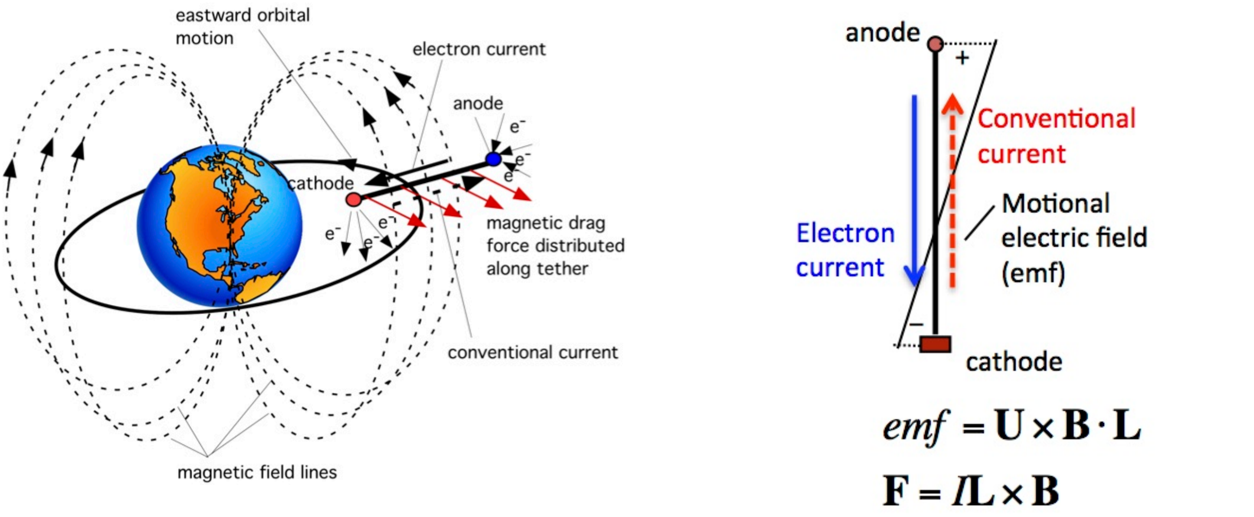
Twenty tethered systems have flown in space starting from with the Gemini-Agena tether experiments in the 1960s. The tether length in the 20 flights ranged from 30 m in the Gemini-Agena to 20 km for the Shuttle-based tethered satellites TSS-1 and TSS-1R and the Delta-based SEDS-I and SEDS-II missions, up to 32 km for the Photon-based YES-2 mission. Ten of the 20 missions used electrodynamic (conductive) tethers (EDT) while in the other 10 missions the tether was non-conductive.

Tethered systems can play important roles in space transportation, space science, human habitation in space, planetary exploration. Specifically for this paper, electrodynamic tethers have particular value for in-space transportation and planetary exploration as these systems can generate forces without needing propellant by exploiting the magnetic field and the plasmaphere. To make a few examples, the EDT system can convert the orbital energy into mechanical drag work (i.e, "drag mode") and power on board if a load is present in the circuit.

Figure 1 shows a schematic of an EDT operating in a drag mode with anodic and cathodic terminations in which the former is depicted as a spherical collector just for clarifying the concept. If the motional electric field is reversed by making the potential with respect to the plasma positive at the bottom of the tether (for a prograde orbit) by using a power supply then the electron current will flow upward and the Lorentz force becomes a thrust (i.e., "thrust mode").

[1] Professor, Measurements and Aerospace Engineering
[2] Post-doc in Science, Technology and Aerospace Measurements

One important technological advance took place in 1993 (see Ref. [1]) when the bare tether anode was introduced. In this new configuration the ED tether is left bare to act as a long and thin anode that collects the ionospheric electrons on a long portion of its length, i.e., along the portion that is positively biased with respect to the plasma. Besides simplifying the design of the system, bare tether anodes are much more efficient than spherical anodes of equivalent area as the formers collect electrons in the Orbital Motion Limited (OML) regime, leading to ED systems of much shorter tether lengths with comparatively-high currents.



(a) (b)

Fig. 1 (a) electrodynamic tether with anodic and cathodic terminations, and (b) schematic of motional electric field *emf* and Lorentz force F with tether current *I*, orbital velocity *U*, magnetic field *B*, and tether length *L*.

The generation of a drag force that does not require propellant and can operate efficiently in Low Earth Orbit (LEO) is of interest for several applications among which the deorbiting of satellites at the end of their operational life.

From the dynamical point of view, a tether system has two stable equilibrium positions along the local vertical (LV) -- one upward and the other downward -- *in the absence of current circulating in the tether*. However, when the current circulates in the tether, the Lorentz forces play a role that is not simply confined to the deorbiting of the spacecraft but has important effects on the stability of the system attitude dynamics as discussed in the next section.

2. Attitude Instability of Electrodynamic Tethers

The direction of the drag force acting on the tether depends on the direction of the magnetic field and the orientation of the tether. The magnetic field lines do not have a constant orientation with respect to the tether line because the Earth's magnetic field is inclined with respect to the equator and in general the orbital inclination is different from. The excitation of the tether oscillations by the Lorentz forces is not a classical linear excitation that would otherwise produce stable librations of the tether system in the absence of resonant components. The excitation mechanism is more complex and is associated with a coupling between the motions in the orbital plane (in-plane) and in the transverse plane (out-of-plane) that is driven by the electrodynamic forces shifting their orientation with respect to the tether. In a rather counter-intuitive manner, the magnetic field component responsible for this coupling is the radial component (i.e., along the local vertical).

The tethered system would have stable librations about the local vertical (LV) *in the absence of tether current* with two different frequencies in plane and out of plane: $\sqrt{3}\omega$ and 2ω, respectively. A tether current different from zero displaces the tether system from the local vertical but through the coupling between the in-plane and out-of-plane degrees of freedom sets the tether into a periodic motion with frequency equal to the orbital frequency. The system describes periodic orbits (whose sizes depend on the initial conditions) in phase space but these periodic orbits are unstable: a small perturbation away from the periodic orbit will cause the size of the periodic orbit to grow from its initial shape *in the absence of damping* in the system. This instability is independent of the presence of components that resonate with the two frequencies mentioned before. The stability/instability of the motion was analyzed with the help of the Floquet theory in Ref. [2]. The instability can also be understood in energy terms by considering that the electrodynamic forces introduce an increasing energy flow into a tether system that moves along an orbit (in phase space) that departs from a periodic solution. The potential energy G for the tethered system is shown in Fig. 2. A system with zero current displaced from the stable equilibrium point (at $\theta = \phi = 0$) and with zero initial velocity, that is with zero initial kinetic energy T with respect to the LVLH reference frame, will describe a trajectory (i.e., an orbit in phase space) that moves on the energy surface. If the total energy $E = G + T$ is less than the potential level at the saddle point ($G = 3/2$ in this normalized representation) then the oscillation is stable and the trajectory can not surpass the initial value of the potential level G_0.

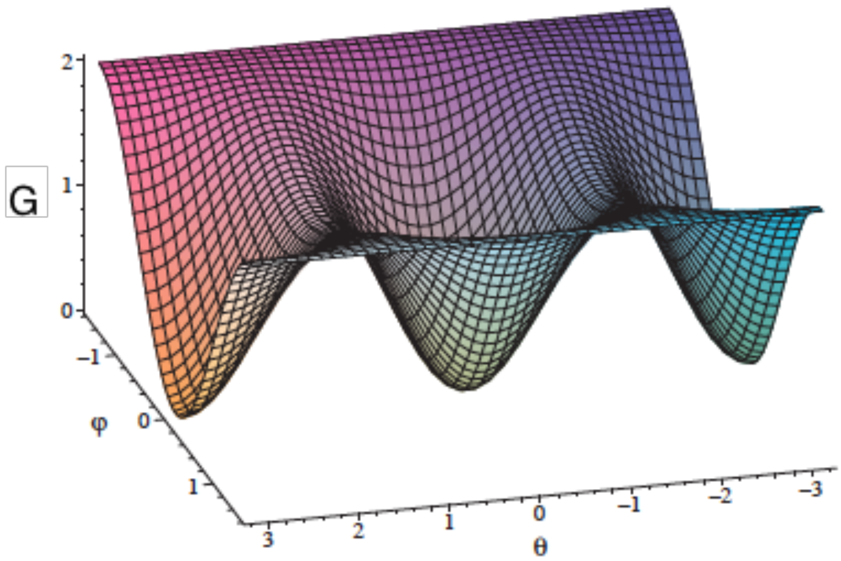


Fig. 2 Potential Energy vs. θ (rad) and ϕ (rad) [Adapted from Ref. 2]

For a tether current different from zero, as mentioned before, the total energy level increases and the phase-space trajectory can at some point in time surpass the initial value of the potential energy and eventually pass the value of the saddle point when the tether libration turns into a rotation.

The growth of the instability depends on ε that is equal to the ratio of the out-of-plane component of the electrodynamic force over the vertical component of the gravity gradient force. For a uniform distribution of the current I_m along the tether and a tether that is all electrodynamic from tip to tip, ε is as follows

$$\varepsilon = \frac{3}{2} \frac{I_m}{m_t + 3m_B} \frac{\mu_m}{\mu} \sin i$$

where m_t and m_B are the tether mass and the tip mass, respectively, μ_m is the magnetic dipole strength, μ is the Earth's gravitational parameter and i is the inclination with respect to the magnetic equator. Since the magnetic field is tilted, the instability occurs also in equatorial orbits and increases with the increasing orbital inclination. However, the maximum current decreases with the increasing inclination so as to mitigate somewhat the dependency on the orbital inclination.

The equation above indicates the strategies for keeping ε small (with a consequent slower growth of the instability): (a) increasing the vertical gravity gradient force; and (b) limiting the tether current. However, equally if not more important is to use means for dissipating the kinetic energy of the tether in order to maintain a safe energy level. This point requires the adoption of either a current control that is able to produce a negative work per oscillation cycle or the adoption of passive mechanical dissipative devices. The options indicated above will be briefly described in the following section.

3. Dynamical Instability Countermeasures

As it has been explained in Section 2, an electrodynamic tether placed in a circular orbit is dynamically unstable over time due to the effects of the vertical component of the magnetic field. This means that the libration angles ϑ and φ will slowly grow until the in-plane angle will reach the 90-deg limit (i.e., when it reaches the local horizontal) and eventually the tether will start to rotate around the mother satellite. In brief, this is due to the constant injection of energy into the system: the electrodynamic forces as mentioned previously are slowly pumping energy into the system. While the electric current can be used to power on-board electronic systems, the hollow-cathode and so on, the increasing kinetic energy is detrimental to the performance of the system and should be limited within a safe level. Luckily, the growth rate of the tether kinetic energy is small [3] and, for deorbiting purposes, it is possible to use countermeasures to maintain the energy below a desired level until the tethered system has reached the reentry altitude, for example 200 km. Once the altitude of the spacecraft has been lowered through ED forces down to such low altitudes, the atmospheric drag will then take over to complete the deorbit.

For the reasons above, our team at the University of Padova has studied and developed several dynamical instability countermeasures as part of team of the FP7-Space project on Propellantless deorbiting of space debris by bare electrodynamic tethers (BETs). In the following paragraphs we briefly describe 5 strategies/devices that can be employed successfully to guarantee a safe and efficient deorbiting using electrodynamic tethers, listed in terms of priority: 1) the tip mass, 2) the inert tether, 3) the in-line damper, 4) the current saturation threshold, and 5) the rotational damper.

A. Tip Mass

The tip mass is a secondary passive spacecraft attached to the tether tip, on the opposite side of the mother satellite. The tip mass increases the restoring torque associated with the gravitational gradient force that is linearly proportional to the term $(m_t + 3m_B)$. For stabilization purposes increasing m_B is three times more effective than increasing the tether mass. Thus, the bigger the tip mass the more stable the tether system. However, the tip mass cannot be increased at will for keeping the desired mass ratio of the EDT system with respect to the spacecraft mass (typically < 5%). For large satellites (mass ≥ 1000 kg) this is not challenging, while for microsatellites the tip mass must be chosen carefully to maintain the system competitive vs. other deorbiting systems [4].

The tip mass can be simply a ballast mass or it can be used to accommodate other subsystems, such as the in-line damper (described later on) or a small propulsive system for aiding the tether deployment [5].

B. Inert Tether

Assuming that the plasma contactor is located on the mother spacecraft, an inert non-conductive tether can be inserted in series between the conductive electrodynamic tether and the tip mass. The adoption of this device has two positive effects on the dynamical stability of the system. The first is the increase of the total mass m_t of the tether while leaving the electrodynamic forces unchanged. The second and more substantial positive effect is that it moves the tip mass away from the mother satellite thus increasing the stabilizing effect of the vertical component of the gravity gradient force (this is not reflected in the simplified expression of ε that was referred to an all-ED tether). The inert tether can be made of a light fiber material. The inert tether increases the overall tether length and mass. An increased tether length increases the flux of micrometeoroid and orbital debris (M/ODs) impacting the tether. In other words, the choice of the inert tether length must be a trade-off between the stability augmentation, the risk to M/ODs impacts, and the system overall mass.

C. In-line Damper

When an electrodynamic tether is turned on the Lorentz forces make it oscillate giving birth to lateral tether vibrational modes (e.g. skip-rope motion, lateral libration) that are the principal sources of dynamical instability. However, relatively-large lateral oscillations are coupled non-linearly with longitudinal tether oscillations. This coupling is actually beneficial because part of the kinetic energy associated with lateral vibrations is transferred to the longitudinal modes of vibrations that are damped by the tether material damping. The material damping mechanism is usually not sufficient for dissipating all the tether kinetic energy. The energy dissipation can be increased substantially by adopting an in-line damper that is tuned to the first longitudinal frequency of the tether. An in-line damper (shock absorber) at the far end of the tether can be attached to or placed inside the tip mass. The device can be simply a short portion of the tether with very low stiffness, like natural rubber, or a mechanism similar to a retractable dog leash. In the latter solution the small reel of the damper is coupled to a viscous wheel, thus providing the energy dissipation as the reel rotates.

D. Current Saturation Threshold

The amplitude of the electrodynamic force is directly proportional to the electric current flowing inside the tether, thus the higher the current the higher the electrodynamic forces. Considering the dependency of the instability on the ε ratio, it is natural to think of a stabilizing device that can control the electric current in such a way as to reduce the instability effects of the Lorentz forces. Several studies have been conducted in this direction trying to design effective current control algorithms that minimizes the negative consequences of the electrodynamic action. For example, the electric current can be reduced to zero (e.g., controlling a resistor inside the current circuit) when the Lorentz forces have the same direction of the orbit motion or when the libration angles have exceeded certain values (see Ref, [6],[7]). Unfortunately, all these solutions require the knowledge of the instantaneous position of the tether with respect to the mother satellite. Those measurements are not easy to implement and the needed additional sensors can considerably complicate the system. For this reason a simpler and effective solution was devised for the BETs system, that is, to keep the electric current always under a certain saturation level. This task can be implemented by simply measuring the instantaneous electric current level without knowing the dynamic state of the tether. This simple algorithm has proven to be very effective in the deorbiting simulations, with the current upper limit depending on the values of tip mass and inert tether length.

E. Rotational Damper

The lateral and the longitudinal motions of a space tether are only non-linearly coupled and an in-line dissipating device such as the shock absorber described in Par. 3-C may be insufficient for the most demanding cases at medium-high inclinations and with long deorbiting times as required by some heavy satellites. In those cases the in-line damper must be supplemented with a rotational damper. In this configuration a rotational damping device is coupled to the attitude motion of the tether. In the context of BETs Project, our team carried out an extensive study on this matter [8],[9]. The damper was conceptualized as a slender and light element (similar to a fishing rod) with a spherical damper located at the interface with the main spacecraft and the tether passing through small rings attached to the rod. The main result of the investigation was that a rotational damper installed between the mother spacecraft and the conductive tether is very effective at damping the tether libration in the most demanding deorbiting cases. For lighter satellites with shorter deorbiting times the in-line damper has proven to be sufficient for stabilizing the tether system [see Ref. 4] during deorbit.

4. The BETs Project: deorbiting performance

In the BETs project [10], the deorbiting performance of a mid-size satellite was extensively analyzed. The goal of the project was to develop an electrodynamic tether system to be attached to new satellites going into orbit and capable of deploying at the end of the operational life of the satellite to provide the propellantless deorbit. The project was a technology development effort involving analysis, conceptual design of the system, developing the strategies for deployment and tether stabilization, building prototypes of key elements like tether samples, deployer, hollow cathode and testing those elements for their functionality. The team also tested extensively the tether samples for their survivability to M/ODs impacts [11] in the hypervelocity impact facility of the University of Padova. The hypervelocity testing proved the far superior impact resistance of tape tethers to impacts with small M/ODs (that are the most common) than cylindrical tethers of some masses.

The solution adopted for stabilizing the EDT during the entire deorbiting was through the techniques mentioned above: (a) sizing of the tip mass, (b) adoption of the inert tether, (c) an in-line damper, (d) a rotational damper, and for the most demanding cases (e) the maximum current limitation. The cases analyzed were for a reference satellite with a mass of 1000 kg starting from a 1000-km-altitude circular orbit at orbital inclinations ranging from equatorial to sun-synchronous.

The analysis was carried out through simulation [12] with a flexible tether model equipped with all the relevant environmental models (gravity field and magnetic field with higher-order harmonics, ionospheric density) and perturbations (solar radiation pressure, atmospheric drag for low LEO, third-body). The simulation model computes the tether current using an Orbital Motion Limited (OML) model that is appropriate for electron collection with a bare-tether anode, the temperature along the tether and accounts for the electrical tether resistance changing with temperature. The deorbiting times vs. orbital inclination are shown in Fig. 3 for an ED tether of 3-km x 25-mm and a stabilizing tether in between ED tether and the tip mass of 3 km, for average solar activity conditions.

The adoption of the various devises/techniques for stabilization has made the deorbiting stable at all orbital inclinations. The deorbiting times range from 1 to 10 months, with the most demanding cases being around 80° of orbital inclination and a reentry time of less than 5 months at sun-synchronous inclination. All the deorbiting times are much smaller than the 25 years specified in the International guidelines for disposing of satellites in LEO. Moreover, an EDT system used for deorbiting reduces significantly the product Cross-SectionxTime (that is a measure of risk) with respect to a neutral-drag deorbiting unlike drag-augmentation devices (e.g., drag sails) that do not have any effect on that product.

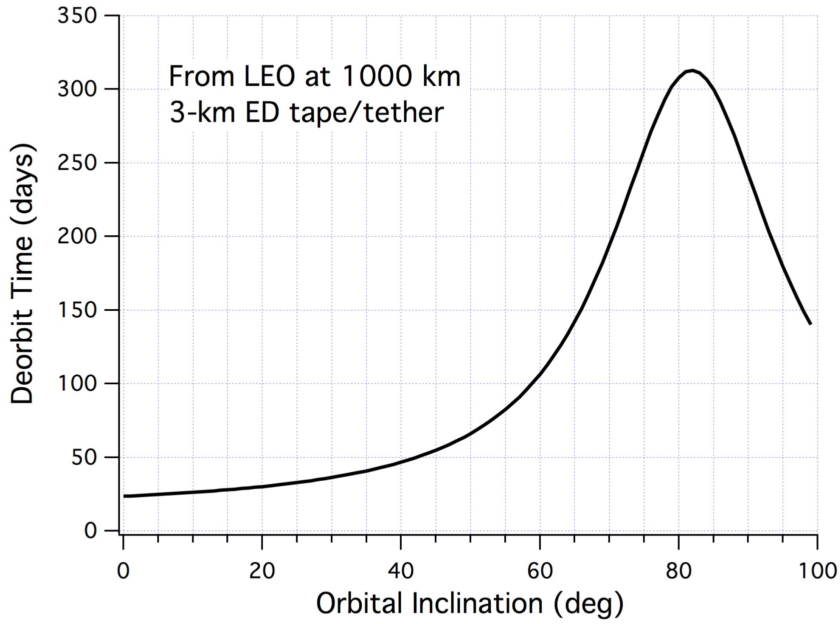


Fig. 3 Deorbiting time vs. orbital inclination for a tethered system with a 3-km x 25-mm EDT attached to a 1000 kg satellite from a 1000-km orbit through reentry for average solar activity

5. Conclusion

Electrodynamic tethers have great potential in several space transportation applications, among which the propellantless deorbiting of satellites at the end of their operational life. The attitude of electrodynamic tethers, however, is subjected to dynamical instabilities produced by the (dragging) Lorentz force through a non-intuitive mechanism that involves the coupling of the motions in the orbital and transverse planes. The understanding of the basis of the instability mechanism and its dependence on the system parameters, which are recalled in the paper, leads to the development of strategies/devices for stabilizing the motion of the system over long duration. Those strategies/devices were utilized in a previous study focused on deorbiting of spent satellites to obtain, through simulation, stable deorbiting of a mid-size satellite from a 1000-km-altiutde circular orbit through reentry at all inclinations with deorbiting times ranging from 1 month to 10 months for the most demanding cases.

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