Aerospace Science and Technology 49 (2016) 112–129

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Libration and transverse dynamic stability control of flexible bare electrodynamic tether systems in satellite deorbit

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 13 November 2015
Accepted 15 November 2015
Available online 8 December 2015

Keywords:
Electrodynamic tether
Dynamic stability
Energy control strategy
Deorbit
Elastic
Thermal and electrical coupling

ABSTRACT

This paper developed a high-fidelity dynamic model of flexible space tether systems by considering the elastic, thermal, and electrical coupling effects on the dynamics and stability of bare electrodynamic tether systems. A simple and effective control strategy based on the libration energy of the flexible tether is derived and applied in the deorbit process. Numerical results show that the newly proposed energy control strategy is effective in controlling the libration and transverse elastic motion of the electrodynamic tether. In addition, the effect of the mass of sub-satellite on the system dynamics and stability is investigated. It is found that the libration and transverse motion of the electrodynamic tether can be stabilized by the proposed control strategy even without the sub-satellite when the electrodynamic force is dominant. This new finding shows the satellite deorbit with the electrodynamic tethers is advantageous in term of mass saving.

1. Introduction

Over the past decades, the number of spacefaring countries and countries capable of launching their own satellites into orbits has increased dramatically. Consequently, the probability of accidental collision among operational satellites and space debris (malfunctioned or end-of-mission satellites and spent rockets) has been increased significantly. Study in 2006 [1] predicted that the current space debris proliferation in the low Earth orbit (LEO) had reached a sufficient density at some altitudes, e.g., 900 km to 1000 km, for the collisions to continue even without any new launches. To address the threat imposed by the space debris, the Inter-Agency Space Debris Coordination Committee recommended removing or mitigating the space debris. One of five mitigation scenarios is to deorbit the end-of-mission satellites within 25 years or by immediate re-entry [2]. Over the years, many technologies [3] have been proposed for the space debris removal, for instance, the chemical propulsion, electrical propulsion, drag sail, solar radiation augmentation sail, tethered momentum exchange, electrodynamic tethers (EDT), laser propulsion, ion-beam shepherd satellite and hybrid EDT ion-beam shepherd systems. Among them, the chemical and electrical propulsion has the highest Technology Readiness Level (TRL) of 9, followed by the EDT with a TRL 6–7 and the rest with TRLs below 5 [3,4]. Compared with the chemical and electrical propulsion, the EDT technology appeals most due to its advantages of low mass, compact size, fuel-less and ease of operation [5]. Particularly, it is able to function independently and does not rely on having a working satellite it resides to re-enter. However, the application of EDT technology is impeded by the unstable libration motion, resulting from the periodic excitation of the electrodynamic force if no control strategy is applied [6,7].

Many studies have been devoted to the investigation of libration stability and control of EDT systems. The dynamic instability of an EDT system is affected by the induced electric current in tether [8]; orbital inclination, altitude and eccentricity [9]; the mass ratio of EDT to main satellite [6], and the transverse dynamic motion of tether [10]. The temperature variation of tether results in additional adverse effects [10,11] on the libration stability due to the thermal stress in tether and the thermal induced variation of electrical and physical properties of tether. In the early studies of libration stability of EDT systems, the dumbbell model was widely adopted due to its simplicity. However, it was revealed that the dumbbell model could not predict the elastic instability of tether, which may lead to the global instability of a tether system faster than the tether libration [12,13]. A tether model consisting of two rigid-bars was proposed to assess the influence of transverse dynamics on the libration stability of flexible tethers in circular [6] or elliptic inclined orbits with high eccentricity [14,15]. Furthermore, a lumped mass model was proposed to capture the high order modes of transverse motion of tether [10]. The analysis results

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http://dx.doi.org/10.1016/j.ast.2015.11.036
1270-9638/

Nomenclature

A_t, A_s	Cross-section or stress area of tether and projected drag area of satellite	m^2
c_m	Specific heat of tether material	$\mathrm{J\,(kg\,K)^{-1}}$
d	Tether diameter	m
e_E	Eccentricity of EDT orbital plane	
E_m	Motional electric field per unit length along the tether	$\mathrm{V\,m^{-1}}$
E	Young's modulus of tether	$\mathrm{N\,m^{-2}}$
H_0	Hamiltonian of tethered system in equilibrium configuration	J
I_t	Electrical current at electron emitter device	A
$L_{e0}(L_e)$	Unstretched length (instant length) of tether element	m
L, L_*	Total and characteristic length of tether	m
n_{orb}	Orbital mean motion	$\mathrm{rad\,s^{-1}}$
$\vec{\boldsymbol{R}}, \vec{\boldsymbol{S}}, \vec{\boldsymbol{W}}$	Unit vector of orbital frame of tethered satellite system	
r	Distance from any point of EDT system to the Earth's center	m
R_{et}	Total electrical resistance in tether	Ω
t	time	
$\vec{\boldsymbol{t}}, \vec{\boldsymbol{n}}, \vec{\boldsymbol{b}}$	Unit vectors of the local frame of tether element	
T, T_0	Instant and initial temperature in Kelvin	K
$\boldsymbol{T}$	Transformation matrix between different coordinate frames	
V_{cc}	Potential bias at the cathodic end C with respect to the ambient plasma	V
X, Y, Z	Components of position vector in global geocentric inertial frame	m
$\alpha, \dot{\alpha}$	Pitch angle, pitch angular velocity of virtual tether	rad
α_{IR}	Infrared radiation absorptivity of tether material	
$\alpha_p, \dot{\alpha}_p$	Periodic solution of pitch angle and angular velocity of virtual tether	rad, $\mathrm{rad\,s^{-1}}$
α_T	Coefficient of linear thermal expansion	
α_s/ε	Ratio of absorptivity to emissivity of the tether	
$\beta, \dot{\beta}$	Roll angle and angular velocity of virtual tether	rad, $\mathrm{rad\,s^{-1}}$
$\varepsilon, \varepsilon_{el}, \varepsilon_{th}$	Total strain of tether, elastic strain of tether and the thermal strain of tether	
θ, θ'	North latitude and co-latitude	rad
λ	East longitude	rad
μ_g	Gravitational constant of Earth	$\mathrm{m^3\,s^{-2}}$
ρ_a, ρ_t	Atmospheric density and material density of tether	$\mathrm{kg\,m^{-3}}$
σ	Electrical conductivity of tether material	$\Omega^{-1}\,\mathrm{m}^{-1}$
$\upsilon, \dot{\upsilon}$	True anomaly and its velocity of system orbital elements	rad, $\mathrm{rad\,s^{-1}}$
$\boldsymbol{\Phi}_t$	Potential bias between tip and gate of Spindt FEA out	V
ω_{orb}	Orbital angular velocity along the W axis in the system orbital frame	$\mathrm{rad\,s^{-1}}$

indicated that the transverse dynamics of a flexible tether is not negligible in the stability analysis of EDTs. Compared to other effects, the effect of thermal perturbation on the libration dynamics and stability of EDTs is relatively less studied. For tethered satellite systems, Williams et al. showed that the temperature variation along the tether strongly influenced the dynamics of capture maneuvers [11]. Yu and Jin found that the thermal effect had a quite different dynamic effect during the retrieval of tethered satellites [16]. For EDT systems, Kawamoto et al. recommended a parametric analysis of EDT stability considering different thermal expansion coefficients of the tether [17]. Furthermore, Zanutto et al. analyzed the orbital descending process by EDTs with consideration of the thermal flux in flexible tethers [10].

In addition to the libration dynamic analysis, many works have been devoted to develop the libration control strategy for the EDT system. Because the libration instability is caused fundamentally by the electrodynamic force pumping energy into the libration motion, it is natural to derive the control strategy based on the system libration energy. The first approach is to reduce the system libration energy by dissipation, for instance, the inclusion of mechanical dissipating [18,19] or wave absorbing mechanisms [20]. The former consists of a conductive tether and a long segment of inert tether combined with an internal damper, while the latter involves a moving tether attachment to weaken the propagation of elastic transverse wave along the tether. The second approach is to control the energy input to EDT systems, such as, the zero net energy input [21] and controlled energy input [22,23]. For instance, William [21] developed a controller based on energy rate feedback with zero net energy input to stabilize the libration of an EDT system. Many other control strategies that track the reference periodic solutions are also based on the same concept. Different from the zero net energy input, Corsi and Iess [22] and Takeichi [23] defined a specific Lyapunov function as a stability function to control the libration motion by bounding the energy input until the EDT system reaches the target deorbit altitude. The last approach is based on the relationship between the electric current and the secular change of orbital elements. For instance, San, Tragesser and Sabey [24,25] developed a control law with feedback of electric current to affect a designed change of orbital elements by current regulation during the orbital maneuvering. These existing control strategies in the published literature provide a good understanding of the peculiar characteristic of EDT systems. Nevertheless, the rigid tether simplification [23,26], the complex design of the energy dissipation mechanism [18,19], and the gross oversimplification in control strategy and continuous electric current control [27,28] impede their practical applications. For the engineering application of EDT concept, the survival probability against the space debris impact is a challenging issue and special attentions should be devoted. Recently, Khan and Sanmartin [29] shows that the tape tether has much high survival probability compared with the single round type tether. Moreover, a design guideline has been suggested by considering the product of the tether-to-satellite mass ratio and the survival probability for a given altitude and inclination [30]. Furthermore, a rule of tether's size optimization has been developed to keep the deorbiting efficiency while avoiding collision with space debris [31].

The present work is aimed to develop a practical and easily implementable control strategy for EDT systems. A high fidelity multiphysics model of EDT systems is developed to investigate the coupled elastic–thermal–electric effects on the libration stability. The elasticity of tether is considered by using the nodal position finite element method (NPFEM) [32,33] while realistic environmental perturbation models are included in the model. Based on the analysis of libration energy of EDT systems, a control strategy is developed to stabilize the libration and transverse dynamic motion of EDT systems while maintaining the deorbit efficiency. The effectiveness of the proposed control strategy is demonstrated by comparison with the existing control strategies [7,22,23,26].