Robust Orbital Boost Maneuver of Spacecraft by Electrodynamic Tethers

Jinyu Liu, Gangqiang Li, Zhenghong Zhu, and Xingqun Zhan*

ABSTRACT This paper presents a coupled multiphysics dynamic analysis for orbital boost maneuver by a fully insulated electrodynamic tether (EDT) and proposes a simplified analytical current-potential circuit equation method to investigate the performance of tether current. Revised Parker-Murphy model is employed to evaluate the electric current generation. This model coupled with the density of electron and atmosphere, and the intensity of Earth's magnetic field. An additional power supply and plasma contactors is necessary. The efficiency of orbital boost maneuver with different radius of contactor and voltage of power supply are compared and contrasted. Through these models, it is shown that tether current is more easily affected by the Earth's magnetic field and plasma density fluctuation. Analysis has determined that this configuration allow orbital boost maneuver from 400 km to 1200 km in 0/30/60/90 degrees initially orbital inclinations. The simulation results show that the 13th-order Earth's magnetic field model affects the orbit parameters of the EDT satellites, especially in an inclined orbit, by changing the orbit from circular to elliptical forms.

Keywords: coupled multiphysics model, electrodynamic tether, libration dynamics, parker-murphy model

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1 Introduction

Tethered satellite system (TSS) basically consists of main-satellite, one or more sub-satellites, and connects each other with tethers [1]. Several TSS missions has been operated for different applications, such as orbital transfer system [2], tether formation system [3], and space elevator [4].There are three types of EDT in the literatures, i.e., bare, partially insulated, and fully insulated EDT. The fully insulated EDT is proposed for orbital transfer boost [5, 6]. This paper investigates the dynamics of orbit boost maneuver by EDT with the coupled multiphysics effects. From the viewpoint of system design, the current generation of EDT system depends on properties of the system and environment parameters, especially the voltage of onboard power supply and the scale of electron collector located at the anode end when the material of tether is determined [7]. Numerical simulation results demonstrate that the coupled multiphysics scheme is capable to realize the interaction of EDT with the surrounding space environment and make the EDT current controllable. Therefore, the EDT satellite system can be used as a 'space debris sweeper'.

2 Libration Dynamics of Electrodynamic Tether

The dumbbell model developed to describe the EDT system. The detailed deduction of this model for the dynamics can be found in [8]. We assumed the Earth is spherical, with non-homogenous mass distribution. The EDT system is based on the right oriented reference frame: the geocentric inertial frame of Earth (o_{xyz}), its origin located at the Earth's center, as shown in Fig. 1.

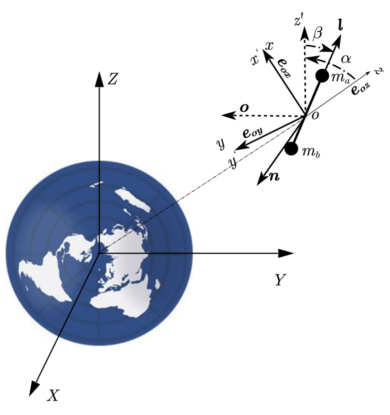


Fig. 1. The reference frame for the motion of EDT satellite system

Considering the EDT as a rigid, long and insulated thin tether length *L*, it connects the main satellite and the sub-satellite. Thus, the tether libration angles α and β can be described as in an orbital frame.

$$\begin{aligned} \ddot{\alpha}+\ddot{\upsilon}-2(\dot{\alpha}+\dot{\upsilon})\dot{\beta}\tan\beta+3\mu r^{-3}\sin\alpha\cos\alpha &= \frac{Q_\alpha}{\tilde{m}L^2\cos^2\beta} \\ \ddot{\beta}+(\dot{\alpha}+\dot{\upsilon})^2\sin\beta\cos\beta+3\mu r^{-3}\cos^2\alpha\sin\beta\cos\beta &= \frac{Q_\beta}{\tilde{m}L^2} \end{aligned} \quad (1)$$

where Q_α and Q_β are the sum of all perturbative torques.

$\tilde{m}=\left(m_a+m_t/2\right)\left(m_b+m_t/2\right)/m-m_t/6$ is the equivalent system mass of EDT system. The torque equation in the orbital frame can be written as

$$\begin{aligned} Q_\alpha &= \int_0^L(\cos\alpha\cos\beta\boldsymbol{e}_{ox}-\sin\alpha\cos\beta\boldsymbol{e}_{oz})\cdot d\boldsymbol{F}(s)=F_\alpha\cos\alpha \\ Q_\beta &= \int_0^L(-\sin\alpha\sin\beta\boldsymbol{e}_{ox}-\cos\beta\boldsymbol{e}_{oy}-\cos\alpha\sin\beta\boldsymbol{e}_{oz})\cdot d\boldsymbol{F}(s)=-F_\beta \end{aligned} \quad (2)$$

where F_α and F_β are the in-plane and out-of-plane components of external forces, respectively.

3 Tether Circuit-Voltage Equations

The electrodynamic force acting on a differential element of EDT $ds, s\in[0,L]$ can be written as

$$d\boldsymbol{F_e}=I(\mathrm{s})\cdot\boldsymbol{s}d\mathrm{s}\times\boldsymbol{B} \quad (3)$$

where $\boldsymbol{B}$ is the local magnetic field strength vector, which components can be described by Legendre polynomials using IGRF2015 model [9] in the spherical frame, such that,

$$\begin{bmatrix} B_r \\ B_\theta \\ B_\phi \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty}(n+1)\left(\frac{r_0}{r}\right)^{n+2}\sum_{m=0}^{n}[h_n^m\sin(m\phi)+\mathrm{g}_n^m\cos(m\phi)]\mathrm{P}_n^m(\tilde{q}) \\ \sum_{n=1}^{\infty}\left(\frac{r_0}{r}\right)^{n+2}\sum_{m=0}^{n}[h_n^m\sin(m\phi)+\mathrm{g}_n^m\cos(m\phi)]\frac{\partial^2\mathrm{P}_n^m(\tilde{q})}{\partial\tilde{q}} \\ \frac{1}{\sin(\theta)}\sum_{n=1}^{\infty}\left(\frac{r_0}{r}\right)^{n+2}\sum_{m=0}^{n}m[-h_n^m\cos(m\phi)+\mathrm{g}_n^m\sin(m\phi)]\mathrm{P}_n^m(\tilde{q}) \end{bmatrix} \quad (4)$$

where r_0 =6371.2 km is the reference radius of Earth, r is the geocentric radius, $\tilde{q}$ =90-latitude is the co-latitude, and ϕ is the longitude. B_r , B_θ and B_ϕ are the components of Earth magnetic field strength. The coefficients g_n^m and h_n^m are the Gaussian coefficients and $P_n^m(\tilde{q})$ means the Schmidt quasi-normalized associated Legendre functions of degree n and order m . we adopted the thirteenth-order inclined magnetic field to analyze the gradual changes of the orbit elements and its in-orbit operation dynamics and libration stability of EDT system, as shown in Fig. 2.

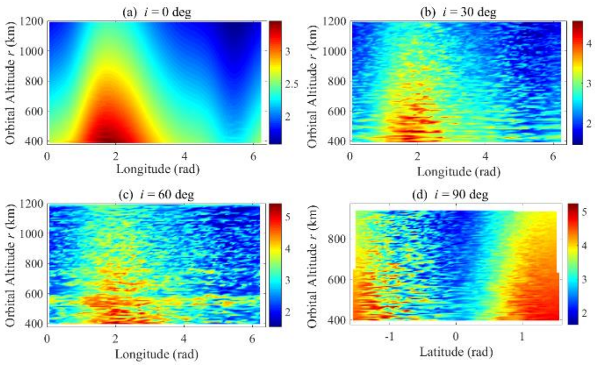


Fig. 2. The intensity of Earth's magnetic field in different orbital inclinations

The electromotive force (*EMF*) along the EDT can be written as,

$$EMF = \int_0^L (\boldsymbol{v_r} \times \boldsymbol{B}) \cdot d\boldsymbol{s} \approx L(\boldsymbol{v_r} \times \boldsymbol{B}) \cdot \boldsymbol{l} \quad (5)$$

where $\boldsymbol{v}_t$ is the equivalent velocity of the center of mass (CM) of EDT. As pointed out in Ref.[10], *EMF* is positive in the thrust mode.

In this paper, the characteristics of current-voltage are described by the revised Parker-Murphy model [12, 13] based on the curve fit of TSS-1R data,

$$\frac{I}{I_0} = \alpha\left[1 + (\frac{\Delta V_a}{V_0})^\beta\right] \quad (6)$$

Here, we take $\alpha = 2.0$ and $\beta = 0.65$.

$$I_0 = A_s e N_e \sqrt{\frac{KT_e}{2\pi m_e}} \quad (7)$$

where $A_s = 2\pi r_s{}^2$ is the surface area projection of the front and back of sphere, r_s is the radius of the anodic collector, e is the electron charge, N_e is the electron density of the plasma, m_e is the electron mass, and K is the Boltzmann constant. The anodic potential normalized to as $V_0 = er_s^{\,2}B^2/8m_e$.

Thus, the tether current-voltage equation for the insulated EDT system can be expressed as,

$$I=\frac{V_s-EMF}{R_t}-\frac{eR_{ac}^2\left(\boldsymbol{B}\cdot\boldsymbol{B}\right)}{8m_eR_t}\left(\frac{I-\sigma_1A_seN_e\sqrt{\frac{k_BT_e}{2\pi m_e}}}{\sigma_1A_seN_e\sqrt{\frac{k_BT_e}{2\pi m_e}}}\right)^{\frac{1}{\sigma_2}} \qquad (8)$$

Thus, the electric current in EDT can be obtained by solving the nonlinear Eq.(8) once the current is determined.

The International Reference Ionosphere (IRI) 2012 model [14] adopt to determine the plasma density, as shown in Fig. 3.

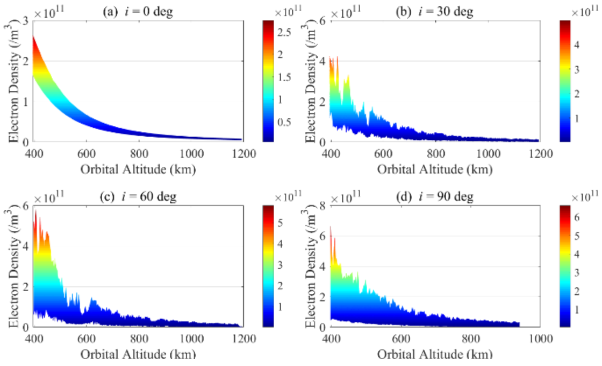


Fig. 3.The electron density in different orbital inclinations

4 Results and Discussion

4.1 System Parameters

Parameters used in this paper came from the TSS-1R mission. For the following simulations, we made some assumptions as follows: 1) the EDT system is initially in a circular orbit at an orbital altitude of 400 km and the targeted altitude is 1200 km; 2) the initial tether libration angles are considered to be zero; 3) the electrodynamic tether keep in a gravity-gradient orientation along the local vertical, be regarded as inflexible rigid rod.

Table 1 parameters of EDT satellite system [15]

Parameters	Value
Tether length L, *km*	20

Tether diameter, *mm*	2.54
Tether mass density, *kg/m*	0.025
Tether electrical resistance, ohms	2100
Mass of main-satellite, *kg*	5000
Mass of sub-satellite, *kg*	500

4.2 Effects of Earth's Magnetic Field and Electron Density

The space physical parameters that influence the amplitude of tether current can be identified in Eq.(8). Here, the external force acting on the EDT system only uses the electrodynamic force.

Effects of Earth's Magnetic Field

The effects of magnetic field on tether current are investigated by assuming the electron temperature T_e = 2321K, and electron density $N_e = 10^{11}/\mathrm{m}^3$, as shown in Fig. 4.

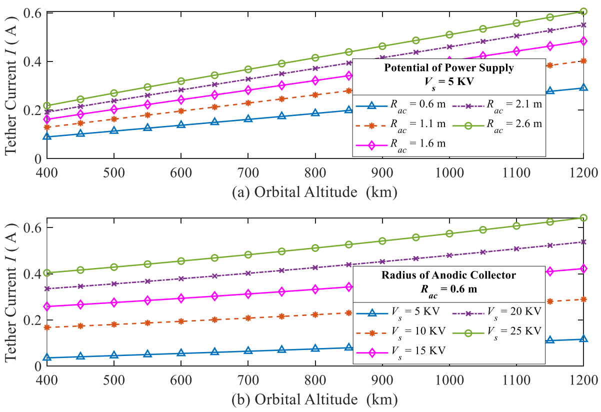


Fig. 4. The EDT current varies with B in equatorial orbit with T_e = 2321K and $N_e = 10^{11}/\mathrm{m}^3$

It is found that the tether current is linearly increased as orbital altitude increases. That's due to the value of electromotive force *EMF* gets smaller, the tether current increases based on Ohm's law.

Effects of Space Electron Density

The effects of electron density on tether current are investigated by assuming the Earth's magnetic field B = 0.3μT and electron temperature T_e =2321K.

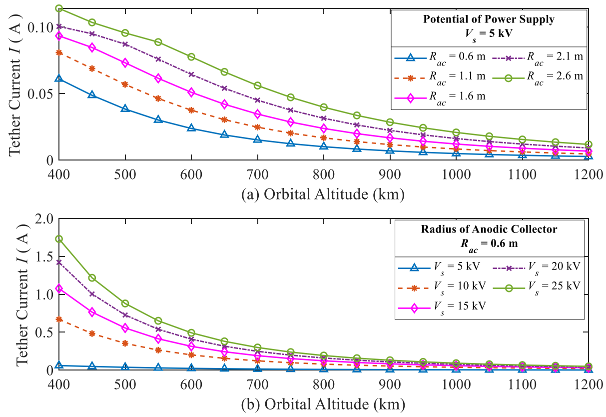
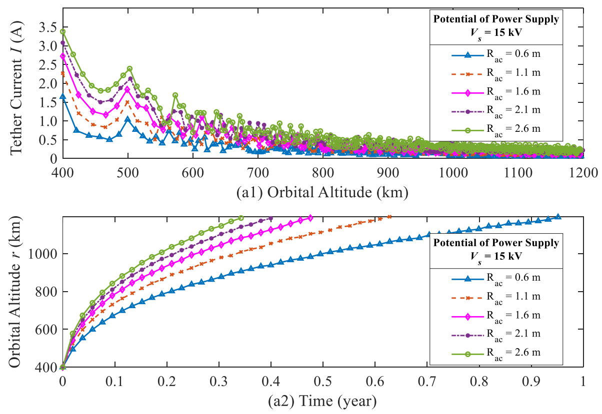


Fig. 5. The EDT current varies with N_e in equatorial orbit with T_e = 2321K and B = 0.3μT

Fig. 5 shows that the amplitude of tether current decreases as orbital altitude increases. This means that electron density is the dominant factor that affects the tether current. As electron density decreases, the tether current rapidly decreases. The current will drop to near 0A when the orbital altitude above 1200 km.

As a result, there are two ways to improve the value of tether current. One is using a larger anode electron collector with a given voltage of power supply, another way is increasing the potential of power supply with a given scale of anode end. Furthermore, the performance of orbital maneuver from 400 km to 1,200 km is investigated, as showed in Fig. 6. As the anode electron collector and the voltage of power supply improves, the amplitude of tether current decreases in Fig. 6(a1) than that in Fig. 6(b1), correspondingly. Therefore, the efficiency of orbital boost maneuver is greatly improved by increasing the potential of power supply, see Fig. 6(a2), Fig. 6(b2).



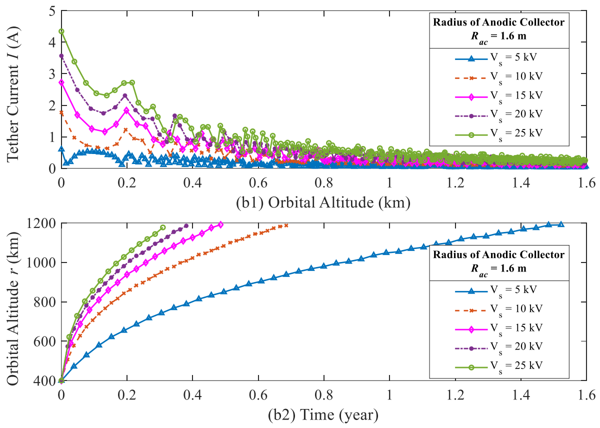


Fig. 6. The efficiency of orbit boost maneuver different R_{ac} and V_s in equatorial orbit

4.3 Libration Characteristics of electrodynamic tether

For the stability of the EDT system, the time history of pitch and roll angles of EDT in different orbital inclinations are investigated, as shown in Fig. 7. It can be found that the libration angles have periodical characteristics. As the increase of orbital altitude, the pitch angle increases slowly, especially in inclined orbit within one year, as shown in Fig. 7(b1)(c1)(d1). Otherwise, the roll angles decrease as the orbital altitude increases within one year, as shown in Fig. 7(b2)(c2)(d2). As for the libration motion of out-of-plane of EDT, the roll angle decreases slowly as the orbital altitude increases. Finally, the roll angle keeps in 5 degrees. Therefore, the EDT system can always in a stable state at the operating period of orbital boost maneuver.

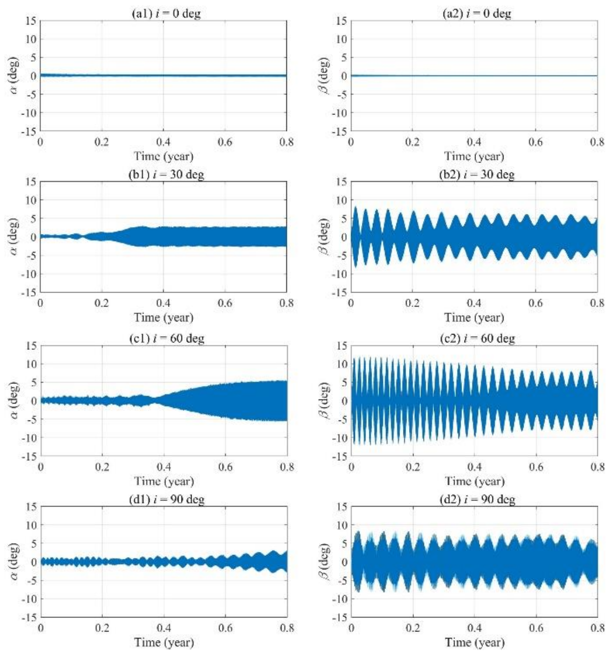


Fig. 7. Time history of pitch and roll angles in different orbital inclinations

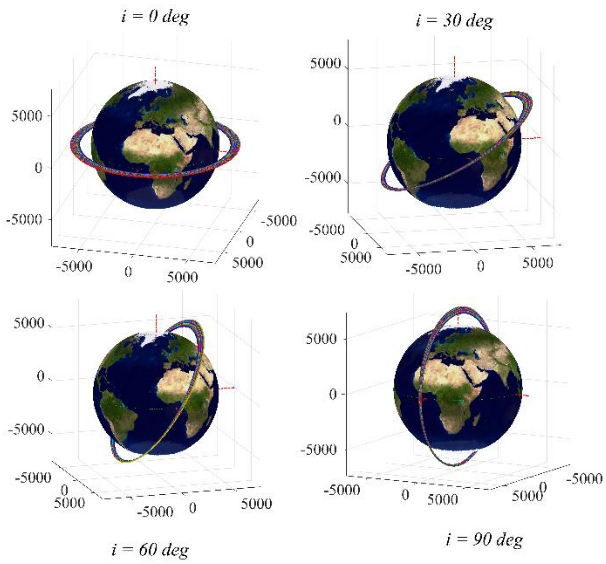


Fig. 8. The time evolution of orbital altitude of EDT system in different orbital inclinations

Finally, we investigate the time evolution of orbital altitude of EDT system in different orbital inclinations, as shown in Fig. 8. It is found that the efficiency decreases as the orbital inclination increases. As shown in Fig. 8 (a) (b) (c), the orbital maneuver time takes about 6 years, the target orbital altitude 1200 *km* has stably arrived in those cases, and the higher orbital inclination needs to longer maneuver times. This means that the orbital maneuver by EDT works better with small orbital inclination. As for a polar orbit, see Fig. 8 (d), the orbital altitude of the EDT system only stayed at 950 *km*. That's because of the reversion of *EMF* polarity of EDT and the weak interaction between the current in the EDT and Earth's magnetic field in the polar orbit.

4 Conclusions

The current work investigated the dynamics of orbital boost maneuver of EDT system by a fully insulated electrodynamic tether propulsion, especially the libration of EDT and it's ambient coupled multiphysics space environmental perturbations were taken into account. In order to analyze the efficiency of orbital boost maneuver, a simplified closed-loop current-voltage equation that based on the revised P-M model is proposed to calculate the performance of anode electron collector. The simulation results demonstrated that the coupled multiphysics model need to be considered in the EDT orbital boost maneuver system. The results provide a full understanding of detailed phenomena in orbital boost maneuver by a fully insulated tether.

Acknowledgments

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