Performance of Electrodynamic Tether De-orbit System on Elliptical Orbit[*][†]

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In this study, the performance of electrodynamic tether deorbit system on elliptical orbit is analyzed by the mission analysis model. Such a system can be used for reducing the space debris in the future. The concept is basically the same as those of preceding studies on circular orbit including ProSEDS space experiment. However, the operation and dynamics are different on elliptical orbit compared with those on circular orbit. Here, we analyze the performance of deorbit system of H-II upper stage on transfer orbit as an example. Then, we discuss about the performance of general deorbit system on elliptical orbit. The analytical results show that this system can deorbit H-II upper stage about in a few months compared with the deorbit time more than 10 years in the case of aerodynamic drag only, although the effective thrust is generated only about 20% of orbit. However, this system is not necessarily advantageous to system mass than chemical propulsion deorbit system on this long elliptical orbit and will be advantageous for the shorter elliptical orbit or the orbit with higher altitude at perigee.

Introduction

The space debris has become major problems in space development at present. For the future safety guaranty of space environment, debris reduction must be accelerated before their collisions or break up phenomena.

The electrodynamic tether generates the deceleration force without propellant by the interaction between the current through the tether and the geomagnetic field on orbit and the system with electrodynamic tether descends more quickly from its orbit compared with the deceleration by aerodynamic drag only. If such a deorbit system (such as Terminator Tether [1]) applies to debris, we can reduce debris on the orbits. For testifying the validity of such a de-orbit system with electrodynamic tether, ProSEDS (Propulsive Small Expendable Deployer System) space experiment [2] is proposed by NASA Marshall Space Flight Center and is planned to fly in 2001. This system is attached to the second stage of Delta II. These previously proposed systems are on circular orbit.

In this study, we examine the possibility of the application of electrodynamic tether to the deorbit of the system on elliptical orbit. As an example, we analyze the performance and the dynamics of elctrodynamic tether deorbit system of used H-II upper stage (Fig. 1). The orbit of spent H-II upper stage is ellipse, 250km at perigee and 36000km at apogee (Fig. 2). Then, we expand the discussion to the general deorbit system on elliptical orbit.

Principle of Electrodynamic Tether Deorbit System

The electrodynamic tether system is constructed with a long conducting tether wire, an end mass (sub-satellite), which straightens the tether wire, and two plasma contactors, which are installed in both

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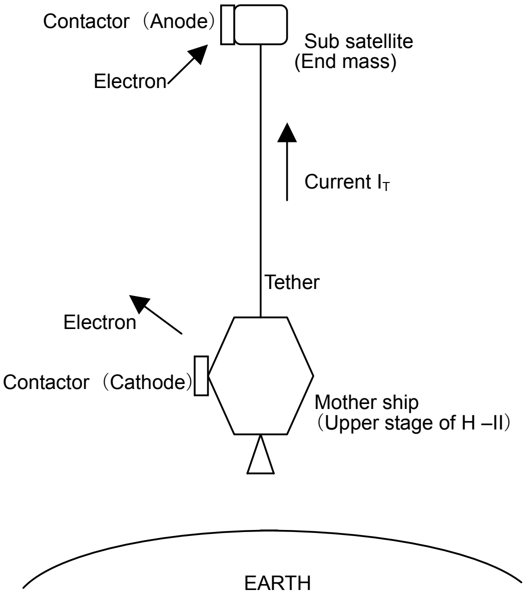


Figure 1 – Electrodynamic tether de-orbit system for H-II upper stage.

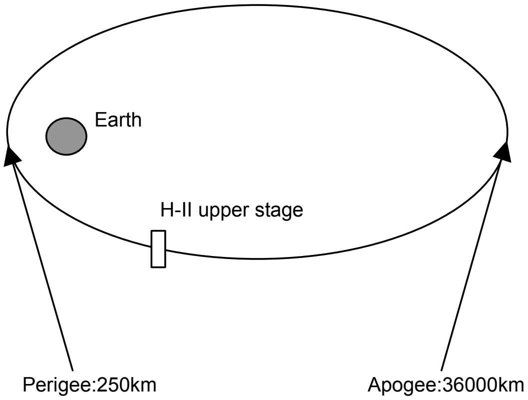


Figure 2 – Orbit of H-II upper stage.

ends of tether wire to form the closed electrical circuit through the ambient ionosphere.

When the conductive tether across the geomagnetic field, the voltage is induced between two ends of tether. This induced voltage is,

$$V_T = L \cdot v \cdot B_H \tag{1}$$

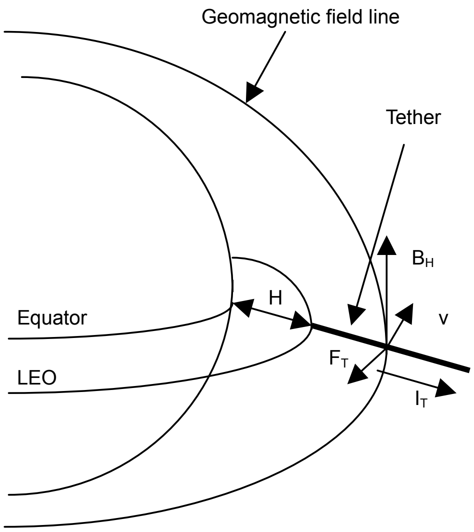


Figure 3 – Principle of operation of electrodynamic tether.

$$B_H = B_0 \cos\varphi_i \left(\frac{r_e}{r_e + H} \right)^3 \tag{2}$$

where, L is the tether length, v is the velocity of tether, B_H is the horizontal component of the geomagnetic field, B_0: average geomagnetic field strength on the ground (3.5×10^{-5} T), φ_i: inclination of orbit, r_e: radius of the earth (=6378km) and H: altitude of the orbit.

If both ends of tether electrically contact with the ambient plasma, the current I_T flows through the tether in the direction from the earth to the space if the tether moves to the eastward. This current interacts with the geomagnetic field and the Lorentz force is induced in the direction of the westward (Fig.3). This decelerating thrust of tether F_T is,

$$F_T = B_H I_T L \cos\alpha \tag{3}$$

where, α is the angle of tether from the vertical direction of the earth's surface. The current I_T that can be flown through tether is determined by the induced voltage V_T and the resistance in electrical circuit R_T as follows.

$$I_T = V_T / R_T \tag{4}$$

The resistance of electrical circuit of tether R_T is,

$$R_T = R_t + R_a + R_c + R_p \qquad (5)$$

where, R_t is the resistance in the tether, R_a is the resistance at anode contactor, R_c is the resistance of cathode contactor and R_p is the plasma resistance surrounding tether. R_t is determined by the tether length and the section area. R_a and R_c are determined by the interaction between contactor plasma and the ambient plasma. The analysis of Hastings [3] is used for obtaining R_a and R_c. R_p is determined by the radiation impedance that generates when the conductive tether moves in the plasma. This radiation impedance depends on the size of the contactor plasma. We assumed that the contactor plasma was sphere, and the analytical method of Benett [4] is used to determine R_p with combining the analytical model of contactor plasma that we use this model to determine the size of the contactor plasma.

In this study, the current through the tether is generally determined by the induced voltage in tether and the resistance in electrical circuit, but the current limit by the ability of plasma contactor is assumed.

The mass of the electrodynamic tether system M_0 is,

$$M_0 = M_{TE} + M_{CO} + M_{EM} + M_{CE} \qquad (6)$$

where, M_{TE} is the mass of the tether wire, M_{CO} is the mass of contactors, M_{EM} is the end mass and M_{CE} is the mass of communication equipment. M_{TE} is determined by the density of tether material, tether diameter and length. In this study, we assumed that M_{CE} and M_{CO} are included in M_{EM}.

If there is the angle of tether for the vertical direction of the earth's surface, the effective thrust for deorbit in the direction of the orbit decreases. The tether angle from the vertical direction of the earth's surface, α, is determined by the balance of the gravity-gradient torques, T_{GT} and T_{GB} that acts on the tether and the end mass and the electrodynamic torque, T_E, that acts on tether (Fig. 4), and is obtained by the following equation.

$$\alpha = \sin^{-1}\left[\left(\frac{B_H{}^2 L r^2}{6 R_T v}\right)\left(\frac{1}{M_{EM} + M_{TE}/4}\right)\right] \qquad (7)$$

where, r is orbit radius.

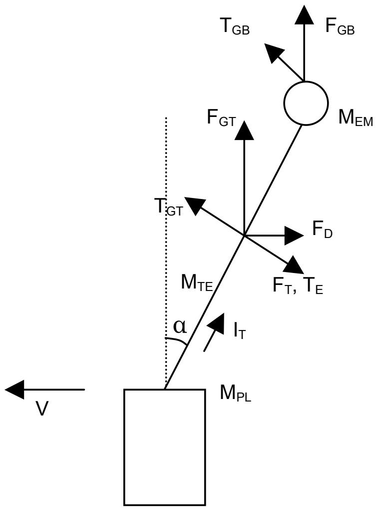


Figure 4 – The balance of the gravity-gradient torque that acts on the tether and the end mass and the electrodynamic torque that acts on tether.

Mission Analysis Model

In this study, we consider the simple two-dimensional motion on the equatorial plane limited to the two bodies problem between the earth and the deorbit system on elliptical orbit and ignore the effect of solar flux pressure. So, the simple analysis by using the equations of elliptical orbit and energy and velocity of the system on the orbit is used to determine the altitude of the system. Basically, the variation of ellipse shape (eccentricity, semi-major axis, perigee radius, apogee radius) is obtained from the variation of system energy determined by the decelerating force per time step.

Model of Aerodynamic Drag

The aerodynamic drag on the orbit was determined by the density distribution model in upper atmosphere by CIRA [5] and the cross section area of the system. The cross section area of tether is determined by its length and diameter. The maximum cross section area (the cross section area of side direction) is assumed for the system to deorbit. The value of drag coefficient of 2 [6] is used in this study.

Assumption of the Analysis

As an example for the system to deorbit on elliptical orbit, the analysis is performed for the upper stage of

H-II with following specifications.

Length: 9.2 m
Diameter: 4 m
Mass: 3 t
Orbit: ellipse (250 km at perigee
and 36000 km at apogee,
0° inclination)

The tether is assumed as follows.

Length of conductive tether: 10 km
Diameter of conductive tether: 2 mm
Material of tether: aluminum
Plasma contactor (anode, cathode):
 Hollow cathode,
 Maximum current: 10 A
Working fluid of contactor:
 Argon, flow rate: 4.5 kg/A/year
End mass of tether system: 100 kg

The diameter and length of tether are selected as the optimum values that were determined by the trade-off between the reduction of mission duration and the reduction of system mass from the analytical results.

The possibility of tether cut by debris during mission is also analyzed by using ORDEM96 model [7] that is recently developed by NASA.

Analytical Results

Figure 5 shows the variation of impedances on tether. When the altitude increases, the collection of electrons becomes difficult because of the decrease of plasma density, but the mobility of electrons increases because of the decrease of magnetic field strength, and the latter effect is larger than the former effect. So, the impedance at anode and plasma impedance decrease with the altitude and the largest impedance was obtained at perigee. Basically, the impedances at cathode and anode and the plasma impedance are not so high compared with the impedance in tether as long as the tether diameter keeps small for the reduction of total system mass. It is necessary that the plasma cloud will be large for small plasma impedance, specially, at high altitude. The radius of plasma cloud is 50m at 6000 km altitude in the analytical results and this value is small enough compared with the tether length and acceptable. On the other hand, the induced voltage rapidly decreases with altitude because of the decrease of magnetic field strength.

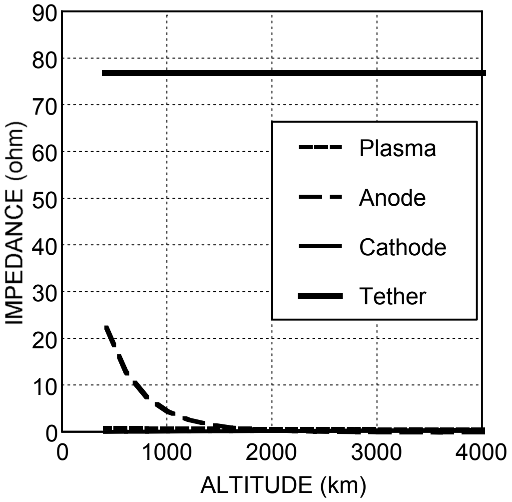


Figure 5 – Variation of impedances on tether.

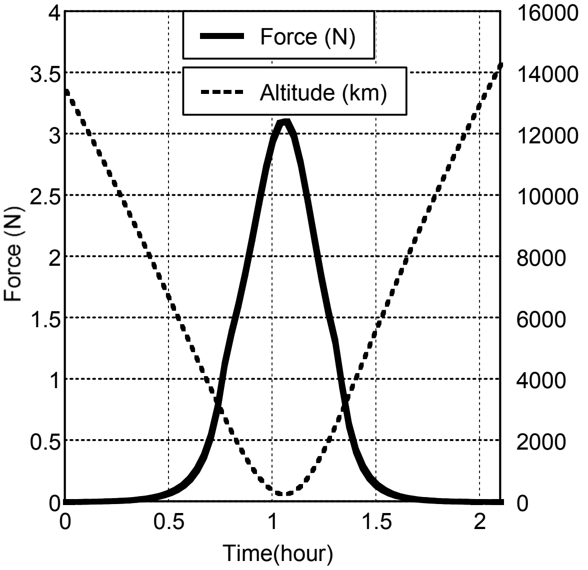
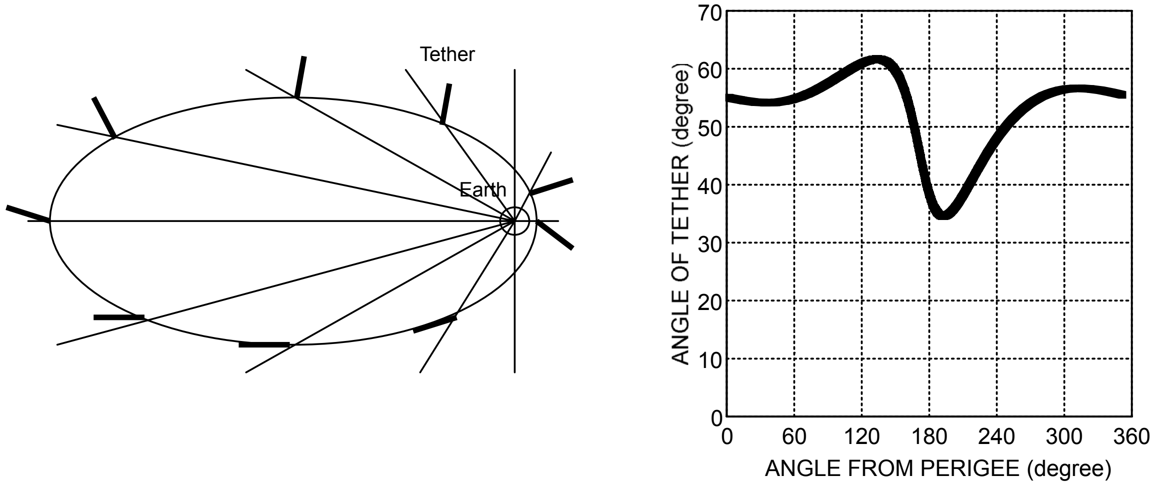


Figure 6 – Variation of tether thrust.

Figure 6 shows the variation of thrust of tether during an orbit circulation. The maximum thrust of about 3N is generated by this system, but the thrust decreases rapidly with increasing altitude because the induced voltage and the current through the tether becomes small with the decrease of the geomagnetic fields at higher altitude. The effective thrust is generated until the altitude of about 6000km, which are about 20% of orbit.



(a) Conceptual figure. (b) Tether angle values

Figure 7 – Variation of tether angle during orbit circulation.

Figure 7 shows the variation of tether angle during an orbit circulation. The tether angle changes complexly for the variation of force balance on tether during orbit circulation and the thrust component along the orbit direction is depressed to about 60 % of that without tether angle.

Figures 8 shows the analytical result of the variation of altitudes of the system at perigee compared with the case of deorbit of systems with aerodynamic drag only. If the electrodynamic tether is used, the deorbit of H-II upper stage can be done in about 65 days if there is no tether angle. It takes about 110 days for deorbit if the effect of variation of tether angle is considered, but this time is still much faster compared with the case without electrodynamic tether system in which it takes more than 10 years for deorbit. This quick descent is due to the combined effect of electrodynamic drag and aerodynamic drag and shows that the electrodynamic tether system still effective for the deorbit of the system on elliptical orbit although the range of generation of effective thrust is limited. The possibility of tether cut by debris during the mission is about 0.02, so the risk with long tether will be ignored.

The deorbit of the system at perigee on elliptical orbit can be done by that the second stage of H-II carries an additional propellant for deorbit and is fired again at apogee. If 450 seconds is assumed as the specific impulse, the additional mass of propellant for deorbit (for the decent from 250 km to 100 km at perigee) is only 10kg. This mass is much smaller than that of tether system (90kg for 10km length tether system).

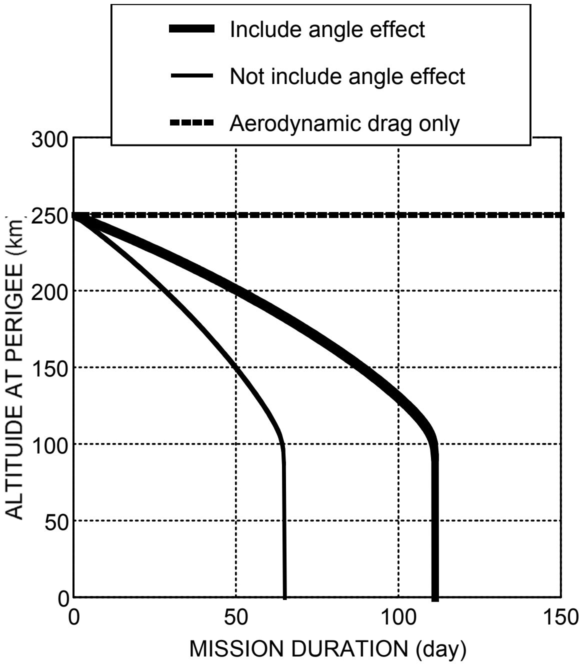


Figure 8 – Variation of altitudes of system at apogee.

So the tether deorbit system is not necessarily advantageous for the deorbit of used chemical propulsion system on this long elliptical orbit if the chemical propulsion system can be restarted and the tether system is disposable. Figure 9 shows that the comparisons of the system mass of tether deorbit system and the propellant mass of chemical propulsion for deorbit when the altitude of perigee is changed.

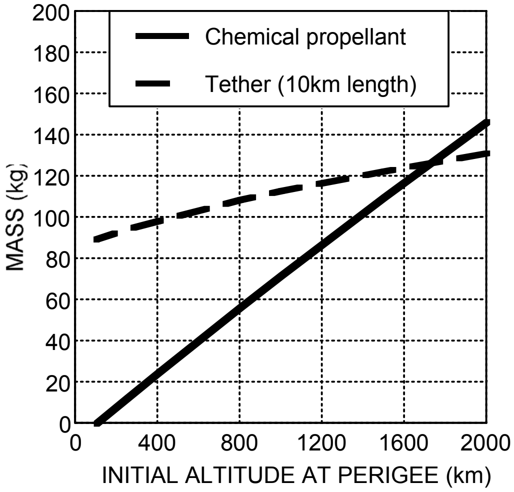


Figure 9 – Comparison of system mass of tether deorbit system and propellant mass of chemical propulsion for deorbit when altitude of perigee is changed

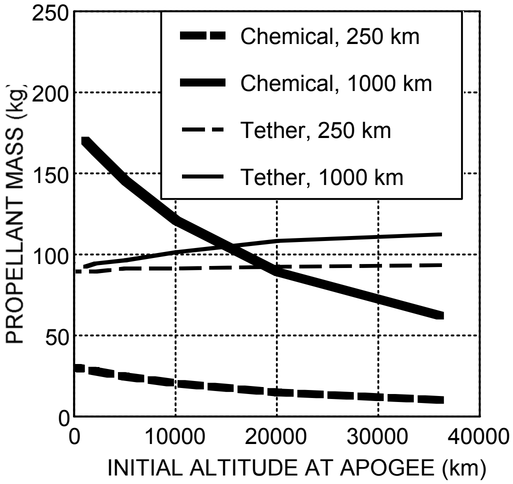


Figure10 – Propellant mass of chemical propulsion for deorbit when the altitude of apogee is changed.

Figure 10 shows that the propellant mass of chemical propulsion for deorbit when the altitude of apogee is changed. These figures show that the tether deorbit system will be advantageous for the shorter elliptical orbit or the orbit with higher altitude at perigee. Of course, if the chemical propulsion system cannot be restarted and the additional propulsion system is necessary for deorbit, the tether deorbit system will be one of more attractive deorbit system even for long elliptical orbit.

Summary

The performance of electrodynamic tether deorbit system on elliptical orbit is analyzed by the mission analysis model. As an example, the electrodynamic tether deorbit system can deorbit H-II upper stage on elliptical orbit (250km at perigee and 36000km at apogee) about in a few months by the combined effect of the electrodynamic force and the aerodynamic force, although it takes more than 10 years for the deorbit of this H-II upper stage if only the aerodynamic force acts on the system. However, this system is not necessarily advantageous than chemical propulsion deorbit system on this long elliptical orbit and will be advantageous for the shorter elliptical orbit or the orbit with higher altitude at perigee.

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