Preliminary Analysis on the Quick Disposal of Used H-II Upper Stage by Electrodynamic Tether

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This study proposes an application of the electrodynamic tether to deorbit a spent H-II upper stage to reduce space debris. In such an application, the induced current flows through the tether wire by the tether motion that intersects the geomagnetic field, and the Lorentz force is induced in the opposite direction of tether motion, namely, the direction of the decelerating system, by the interaction between this induced current and the geomagnetic field. The concept is basically the same as that of a ProSEDS space experiment, which is proposed by NASA's Marshall Space Flight Center. But the main difference is its orbit. The orbit of spent H-II upper stage is ellipse, although the orbit of ProSEDS is circular. So the operation and dynamics are different compared with those of ProSEDS. In this study, the performance of an H-II upper stage deorbit system by electrodynamic tether is analyzed by the mission analysis model, and the presumable dynamics of this system is also shown. The results show that this system can deorbit an H-II upper stage in a few months, but there is a possibility that the performance of deorbit will degrade if a rotation of the tether system is occurred.

Key Words: Debris, Environment, H-II, Simulation, Space Engineering, Tether

1. Introduction

A space tether system has a variety of applications such as microgravity realization by isolating the vibration of moving parts, artificial gravity generation by rotating two bodies connected with a tether, scientific measurements of the upper atmosphere by multiprobes on the long tether, momentum exchange orbit transfer by releasing a payload connected with a long tether from the mother ship, and electrodynamic orbit boosting or deboosting by the interaction between tether current and a geomagnetic field. In these applications, electrodynamic orbit deboosting can be used for the deorbiting of debris.

Space debris has become a major problem in space development. For the future safety guarantee of space environment, debris reduction must be accelerated before the occurrence of collisions or breakup phenomena.

The electrodynamic tether generates a deceleration force without a propellant by the interaction between the current through the tether and the geomagnetic field in the orbit, and a system with an electrodynamic tether descends more quickly from its orbit compared with deceleration only by aerodynamic drag. If such a deorbit system (such as a Terminator TetherTM ¹⁾) applies to debris, we can reduce space debris. For testifying the validity of such a deorbit system with an electrodynamic tether, a ProSEDS (Propulsive Small Expendable Deployer System) space experiment²⁾ is proposed

by the NASA's Marshall Space Flight Center and is planned to fly in August 2001. This system is attached to the second stage of Delta II.

As the tether group in Japan, we are also considering the deorbit system of a used upper stage of H-II launcher using an electrodynamic tether (Fig. 1). The electrodynamic tether system will be constructed with a long conducting tether wire, an end mass (subsattellite), and two plasma contactors. The end mass straightens the tether wire. The two plasma contactors are installed in both ends of tether wire to form the closed electrical circuit through the ambient ionosphere. The concept is basically the same as that of a ProSEDS space experiment, but the main difference is its orbit. The orbit of spent H-II upper stage is ellipse, 250 km at perigee and 36,000 km at apogee (Fig. 2), though the orbit of ProSEDS is about 400 km circular. In this study, the performance and dynamics of this electrodynamic tether deorbit system of an H-II upper stage are analyzed.

2. Principle of Electrodynamic Tether Deorbit System

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

$$V_T = L \cdot v \cdot B_H \quad (1)$$

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

Fig. 1. Electrodynamic tether deorbit system for H-II upper stage.

Fig. 2. Orbit of H-II upper stage.

where L is the tether length, v is the local horizontal component of the velocity of tether, B_H is the horizontal component of the geomagnetic field, B_0 is the average geomagnetic field strength on the ground (3.5×10^{-5} T), φ_i is the inclination angle of orbit, r_e is the radius of the earth ($= 6,378$ km), and H is the altitude of the orbit.

If the two ends of the tether electrically contact with the ambient plasma, the current I_T flows through the tether in the direction from the earth to space if the tether moves 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 is

$$F = B_H I_T L \quad (3)$$

The current I_T that can be flown through a tether is determined by the induced voltage V_T and the resistance in electrical circuit R_T as follows:

Fig. 3. Principle of operation of electrodynamic tether.

$$I_T = V_T / R_T \quad (4)$$

The resistance of electrical circuit of tether R_T is

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

where R_t is the resistance in the tether, R_a is the resistance at anode contactor, R_c is the resistance at cathode contactor, and R_p is the plasma resistance surrounding tether. The resistance of tether R_t is determined by the tether length and the section area. The resistances at anode and cathode contactors, R_a and R_c , are determined by the interaction between contactor plasma and the ambient plasma. The analysis of Hastings³⁾ is used to obtain R_a and R_c . The plasma resistance surrounding tether R_p is determined by the radiation impedance that generates when the conductive tether moves in the plasma. The analytical result of Wang⁴⁾ is used to determine R_p .

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

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

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. In this study, 150 kg is assumed to be the tether system mass M_0 based on a ProSEDS system.

3. Mission Analysis Model

In this study, we consider the simple two-dimensional motion on the equatorial plane limited to the two bodies problem between earth and the deorbit system of an H-II upper stage and ignore the effect of solar flux pressure. So the simple analysis by using the equations of elliptical orbit and

Fig. 4. Flow diagram of mission analysis.

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, semimajor axis, perigee radius, apogee radius) is obtained from the variation of system energy determined by the decelerating force per time step. Figure 4 shows the program flow of the calculation.

4. Model of Aerodynamic Drag

The Aerodynamic drag on the orbit was determined by the density distribution model in the upper atmosphere by CIRA⁵⁾ 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 upper stage of H-II.

5. Assumption of the Analysis

The analysis in this study is performed for the upper stage of H-II of the following specifications.

Length: 9.2 m

Diameter: 4 m

Mass: 3 t

Orbit: ellipse (250 km at perigee and 36,000 km at apogee, 0° inclination)

The tether is assumed to be as follows:

Length of conductive tether: 5 km, 10 km, 15 km

Diameter of conductive tether: 1 mm

Material of tether: aluminum

Plasma contactor (anode, cathode): Hollow cathode

Maximum current: 10 A

Working fluid of contactor: Argon (flow rate: 4.2×10^{-7} kg/A/s)

Mass of tether system: 150 kg

The diameter of the tether was determined as the diameter at which the current through the tether is about 10 A by the induced voltage at an altitude of 250 km.

6. Analytical Results

Figure 5 shows the variation of tether thrust during the first orbit's circulation in the case of a 15 km tether length. The maximum thrust of about 5 N is generated by this system, but the thrust decreases rapidly with increasing altitude because of the decrease of induced voltage, namely, the decrease of the current through the tether (Fig. 6) with the decrease of the geomagnetic fields. The effective thrust is generated until an altitude of about 6,000 km. This range is

Fig. 5. Variation of thrust of tether.

Fig. 6. Variation of impedance and current of tether.

Fig. 7. Variation of altitude at perigee.

Fig. 8. Variation of altitude at apogee.

Fig. 9. Effect of electrodynamic drag and aerodynamic drag.

about 20% of orbit.

Figures 7 and 8 show the analytical results of the system's variation of altitudes at perigee and at apogee for different tether lengths compared with the case of a deorbit of systems with aerodynamic drag only. These figures show that the decrease of the altitude at perigee is much smaller than that at apogee. This is a characteristic nature of elliptical orbit. If the electrodynamic tether is used, however, the deorbit of the H-II upper stage can be done in about 80 days when the tether length is 15 km. This is much faster than without an electrodynamic tether system, in which it takes more than 10 years for deorbit. The deorbit time depends on the length of the tether, and it takes about 250 days in the case of

the same length of a ProSEDS system (5 km). This value is large compared with the deorbit time of a ProSEDS, which is about two weeks. However, the electrodynamic tether system is still effective for the deorbit of the system of an elliptical orbit, though the range of generation of effective thrust is limited.

Figure 9 shows how much the electrodynamic drag force contributes to the deorbiting of the system when the tether is 15 km long. If there is no aerodynamic drag, it takes about 120 days for the system to deorbit. This means that the quick descent by electrodynamic tether system is due to the combined effect of electrodynamic drag and aerodynamic drag.

Fig. 10. Rotation of tether on elliptical orbit.

7. Rotation of the System

There is a possibility of a problem for the system in elliptical orbit that the rotational motion of the system is induced by the strong gravity gradient torque that acts on the perigee. Figure 10 shows the analytical result of the dynamics of rotation of the tether system. The earth is at the point (0, 0) in the figure. In the model, the mother ship of 3 t, the subsatellite of 50 kg, and the tether of mass less hinge were assumed. The initial tether attitude angular velocity of 6×10^{-4} rad/s was given. If such a rotation occurs, the thrust component in the direction of the decelerating system decreases. In the worst case, the deceleration force is canceled by the acceleration force that is generated when the tether overturns. This worst case can be avoided by operating contactors reversibly and generating deceleration force at all times. However, there is another possibility in which the average thrust greatly reduces when the tether directs in a direction parallel to the earth near the perigee (see the right hand figure of Fig. 10), compared with the thrust when there is no rotation.

The forces that act on an electrodynamic tether are complicated. So it is necessary to analyze the dynamics of tether in more detail in the future to determine in what situations such a rotational motion will occur or what countermeasure is necessary to avoid such a rotational motion.

8. Summary

The performance of an H-II upper stage deorbit system by electrodynamic tether is analyzed by the mission analy-

sis model. The orbit of H-II upper stage is ellipse, 250 km at perigee, and 36,000 km at apogee. It takes more than 10 years for the deorbit of this H-II upper stage if only the aerodynamic force acts on the system. If the electrodynamic tether is used, however, the deorbiting of this H-II upper stage can be done in a few months by the combined effect of the electrodynamic force and the aerodynamic force. The presumable dynamics of this system is also analyzed. The results show that a possibility exists of degradation of the deorbit performance if the rotation of the tether system occurs. The further detailed analysis is necessary to determine the relation between such tether dynamics and performance.

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