Performance of Electrodynamic Tether Orbit Transfer System with Consideration of Lifetime by the Impact of debris

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Abstract

The performance of electrodynamic tether orbit transfer system was analyzed with the consideration of lifetime by impact of debris to examine its possibility of the application to the round trip transportation mission between low earth orbits. The mass, the electric power and the mission time of tether orbit transfer system were obtained by the principle of operation of electrodynamic tether and the mission analysis based on the simplified orbit transfer analysis model of ion thruster for representative parameters and were compared with that of ion thruster orbit transfer. The lifetime of tether was obtained by the debris model of ORDEM96 of NASA and the relation of impact cross section between wire and projectile. The results showed that there is a lower limit of mission time for each altitude of arrival orbit or higher limit of altitude of arrival orbit for each mission time and there are the proper operating conditions for each parameters of tether system. The results also showed that the tether orbit transfer system had mass advantage compared with the ion thruster orbit transfer system for the same missions.

Introduction

In the future, as the space development is activated and the necessity of large-scale transportation increases, the low propellant consumption will be required for the propulsion system of orbit transfer vehicle from the point of views of the conservation of resources and the protection of terrestrial environments.

The electrodynamic tether is constructed with the long conducting wire, power generator and contactors which are installed in both ends of tether wire to form the closed circuit through the ionosphere, and can be used as a thruster by the Lorentz force generated by the interaction between the current flows through the tether wire and the geomagnetic field. So, the electrodynamic tether is one of the most attractive propulsion systems because it can be propelled without propellant.

There are many studies about electrodynamic tether [1]. The study including the application of propulsion was performed by Hastings [2]. He studied the performance of the application of electrodynamic tether to the power generation, the drag compensation and the orbit altitude change for the Space Operation Center, which was an early space station design by NASA. But there is no study about the application of electrodynamic tether to general orbit transfer system.

In this study, the detail analysis of the performance of electrodynamic tether orbit transfer system with considering the effect of debris impact is performed to examine its possibility of the application to the transportation between orbits and to propose the design guidelines of the system for maximizing its performance.

Principle of Operation of Electrodynamic Tether

If the current flows in the tether wire in the geomagnetic field, the Lorentz force is induced by the interaction between the current and the geomagnetic field (Fig.1). The thrust of tether $F_T$ is

$$F_T = B_h IL$$

(1)

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

(2)

where, $B_h$: horizontal component of geomagnetic field, $I$: current in tether wire, $L$: tether length, $B_0$: average geomagnetic field strength on the ground ($3.5 \times 10^{-5} T$), $\varphi_i$: inclination angle of orbit, $r_e$: radius of the earth (=6378km), $H$: altitude of the orbit.

The electrical circuit between the tether wire and the ambient plasmasphere is closed through electrons which are collected and emitted by the plasma contactors installed both ends of the tether wire.

In this study, the mass and the power of electrodynamic tether orbit transfer system are evaluated for various parameters.

The power of the electrodynamic tether system $P_w$ is,

$$P_w = \frac{V_0 I}{\eta_p}$$

(3)

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where, \( V_0 \) is the voltage drop in tether system, \( I \) is the current through tether wire and \( \eta_p \) is the power utilization efficiency. In this study, 0.9 is assumed as \( \eta_p \).

The total system voltage drop \( V_0 \) is,

\[
V_0 = B_0 IL + IR + IR_p + \Delta V_a + \Delta V_c
\]  
(4)

where, \( B_0 IL \) (\( v \) is the tether velocity) is the induced voltage which is generated by the motion of tether through the geomagnetic field, \( IR \) is the voltage drop in the wire (\( R \) is the resistance in the wire), \( IR_p \) is the voltage drop in the plasmasphere (\( R_p \) is the resistance in the plasmasphere), \( \Delta V_a \) is the voltage drop of the anode contactor and \( \Delta V_c \) is the voltage drop of the cathode contactor. The voltage drops of the contactors \( \Delta V_a, \Delta V_c \) are derived from the theoretical current equations between the plasma crowd formed by contactor and the ambient plasma in the ionosphere \[3\]. The resistance of plasmasphere \( R_p \) is obtained by the analysis of radiation impedance in the plasmasphere \[4\].

The mass of the electrodynamic tether system \( M_0 \) is,

\[
M_0 = M_{PL} + M_{TE} + M_{CO} + M_w + M_S
\]  
(5)

where, \( M_{PL} \) is the payload mass, \( M_{TE} \) is the mass of the tether wire, \( M_{CO} \) is the mass of contactors, \( M_w \) is the mass of power generator, and \( M_S \) is the mass of structures. The mass of tether wire \( M_{TE} \) is determined by the wire diameter and the assumed wire length. The tether wire diameter is determined by the equilibrium of heat input and output in the wire. However, if the possibility of cut of tether by debris in mission time is larger than 1, the wire diameter is reset to larger diameter that the possibility of cut of tether becomes less than 1. The material of tether wire is aluminum. The hollow cathode is assumed as the contactor and the mass per current of 5kg/A \[3\] is assumed based on the ion thruster technology. The argon is assumed as the working fluid of contactor and its flow rate is \( 4.2 \times 10^{-3} \) kg/A/s. 20kg/kW and 8kg/kW are assumed as the specific masses of solar power generator and the structures, respectively, based on those of the electric propulsion system \[4\]. So, \( M_{CO}, M_w \) and \( M_S \) are obtained when the current and the power of the system are determined.

**Debris Model**

One of the large problem for using tether system in space is the possibility of the cut of tether wire by the impact of orbital debris, because the tether diameter is small, generally less than a few millimeters, and its length is large, generally more than a few kilometers.

ORDEM96 \[3\] is used as the orbital debris model. This model is the most recent model of orbital debris developed by NASA. Figure 3 shows the relation between the debris diameter and the estimated debris flux distribution for different altitude in year 2020.

The possibility of cut of tether, \( N_t \) in mission time \( T_m \) is,
Fig. 3 Estimated debris distribution in 2020.

\[ N = \int_0^t F(X(D_{DE}, H)) \times L \times (D_{TE} + D_{DE}) \times N_{TE} dt \]  

(6)

where, \( F(X) \) the debris flux for the debris diameter of \( D_{DE} \) at altitude of \( H \), \( L \) tether length, \( D_{TE} \) tether diameter, \( N_{TE} \) number of tether.

Some experiments of impact between wire and high speed particle shows that the wire with the diameter of \( D \) will cut the particle of the diameter of \( D/3 \) \(^{[6]} \). So, \( D_{DE} \) is assumed to \( D_{TE}/3 \).

**Mission Analysis Model**

It is assumed in this study that the mission is round trip in which the system transports the payload from lower initial orbit to higher arrival orbit and returns without payload to lower initial orbit. The thrust at the initial orbit is determined by setting the current through the tether \( I \). It is assumed that the current is kept at constant value in the mission, so, the thrust decreases with the increase of altitude. In the trip returns to lower orbit, the current is reverse, but the absolute value is the same as the trip to higher orbit.

The mission time is determined from the mission analysis based on the analysis of electric propulsion orbit transfer system \(^{[7]} \). This model is the two dimensional model on the equatorial plane limited to the two bodies problem between the earth and the spacecraft, and includes the effect of shadow of the earth but not include the effects of drug in the atmosphere, the solar flux pressure and the degradation of solar cells. The original model is the constant thrust model, but the model was modified to variable thrust model to fit tether analysis.

The other assumptions and parameters in this analysis are as follows.

<Assumptions>
Payload mass; 1000kg

Altitude of initial orbit; 500km
Limit value of temperature of tether; 303K
Heat radiation rate of tether wire surface; 0.85
Radius of plasma cloud of contactor; 3m
Electron temperature in the contactor plasma; 2eV

<Parameters>
Altitude of arrival orbit \( H \); 2000, 3000, 4000, 5000, 6000km
Length of tether wire \( L \); 2.4, 6, 8km
Number of tether wire \( NT \); 1, 2, 3, 4
Mass flow ratio of working fluid of contactor \( \varepsilon \); 0.18, 0.21, 0.28, 0.35, 0.7
Current through tether \( I \); 1~10A

The mass flow ratio of working fluid of contactor is the ratio of the actual mass flow rate of anode contactor to the flow rate that is necessary to obtain the tether current by ion current only. The plasma cloud that is produced by anode contactor can collect the electron current from ambient plasmaphere. So, it is not necessary to flow full flow rate equivalent to tether current. In this study, the ionization rate of 100% is assumed. Number of tether is a number of tether wire for thrust. In this study, we assumed that all tether systems carry one auxiliary tether wire for the case tether is cut by debris.

**Analytical Results**

Figure 4 shows the relation between the mission time and the tether system mass for different altitude of arrival orbit \( H \). The tether is a single tether and its length is 4km, and the mass flow ratio is 0.28. The system mass increases with the increase of altitude of arrival orbit for the same mission time or with decrease of mission time for the same
system mass described before is mainly caused by the increase of power source. Moreover, the thrust of tether is in proportion to the current through tether wire and the voltages in the tether wire and the plasmaphere are in proportion to the current, so, the increase of thrust brings the quadratic increase of power. So, the rate of increase of system mass increases with the decrease of mission time and the increase of altitude, and there is a lower limit of mission time for each altitude of arrival orbit or higher limit of altitude of arrival orbit for each mission time.

Figure 6 shows the variation of voltage drop of each component at the same current, 5.4 A. The induced voltage dominates the total voltage at low altitudes, but it
The low current condition for long tether. But, its effect becomes ineffective with increasing length because the induced voltage is high for long tether. However, the possibility of impact with space debris increases with increasing tether length as shown in Fig. 8. So, there is an appropriate tether length for the system.

Figure 9 shows the effect of number of tether wire on the system mass. The tether length is 4km, and the mass flow ratio of contactor is 0.28. The altitude of arrival orbit is 3000km. The total cross section area that is necessary to operate in the limit value of temperature of tether can be reduced with the increase of number of tether wire because the current per tether wire decreases and the ratio of surface area to cross section area of total tether wire increases. So, there is a tendency that the system mass decreases with the increase of number of tether. But its effect is small because the mass of tether wire is small compared with the total mass as shown in Fig. 5. In addition, as shown in Fig. 10, the possibility of cut of tether by debris increases with the increase of number of tether because the diameter of tether decreases and the total cross section of tether for debris impact increases. So, the increase of number of tether is not necessarily effective for the system.

Figure 11 shows the effect of mass flow ratio of contactor \( \varepsilon \) on the system mass. The tether is a single tether, and its length is 4km. The altitude of arrival orbit is 3000km. The mass flow ratio much influences on system mass and the system mass increases greatly with the decrease of mass flow rate in the case the flow rate becomes under the equivalent tether current. The shortage of current in the case that the flow rate becomes under the equivalent tether current should be compensated by collecting electrons from the ambient plasma. If the flow rate decreases, namely, shortage of current increases, the voltage drop between the anode plasma and the ambient
plasma increases to obtain larger electron current, and the power of the system, namely, the mass of the system, increases. The mass of working fluid of contactor is very small, 1~5% of total system. So, the contactor of the tether system should operate at larger flow rate where the voltage drop at contactor is not high (in this case, more than about 30% of equivalent tether current).

Figure 12 shows the comparison of the system mass of tether orbit transfer system and the system mass of ion thruster orbit transfer system. It was assumed that the specific impulse of ion thruster was 5000sec, the specific mass of power source was 20kg/kW that was the same as tether system, the specific mass of structure including thruster was 10 kg/kW, the power utilization efficiency is 0.9 and the propellant utilization efficiency is 0.9. The tether is a single tether and its length is 4km, the mass flow ratio of contactor is 0.28.

The electrodynamic tether orbit transfer system is advantageous compared with the ion thruster orbit transfer system for the same missions in the range of long mission time. But, in the case of short mission time, the mass of tether system sharply increases and is to be larger than that of ion thruster system. The performance values of both propulsion systems are shown in Table 1 for the altitude of arrival orbit of 3000km and the mission time of 40 days.

Figure 13 shows the relation between total mass of orbit transfer systems (tether and ion thruster) to the number of round trip in the case of 110 days mission time and the altitude of arrival orbit of 6000km at which the system mass of tether orbit transfer system is larger than that of ion thruster orbit transfer system for one round trip (425kg for tether system and 420kg for ion thruster system). By the way, the mass of chemical propulsion is about 630 kg (575 kg propellant) for one way trip to the same altitude. The total mass of ion thruster orbit transfer system increases largely with the number of round trip because the propellant mass, which occupied about 14% of total system mass, is necessary to supply per trip. On the other hand, the total mass of tether orbit transfer system increases only a little because the consumed mass per trip, the mass of working fluid of contactor, is a little, about 4% of total system mass. The total mass jump for tether system around 8 round trips is by the additional tether mass that is necessary by the possibility of cut of tether by debris around this time (the possibility of impact of debris per one round trip is 0.131 in this case). So, although in the range that the system mass is large for one round trip, the tether
orbit transfer system will be advantageous compared with the ion thruster orbit transfer system for the large number of trip even if considering the mass loss of tether wire by the impact of debris.

**Summary**

The mass, the electric power and the mission time of electrodynamic tether orbit transfer system are evaluated with the consideration of lifetime by the impact of debris to examine its possibility of the application to the transportation between orbits.

As the analytical results, follows are obtained.

(1) There is a lower limit of mission time for each altitude of arrival orbit or higher limit of altitude of arrival orbit for each mission time because the increase of thrust with decreasing mission time or increasing altitude brings the quadratic increase of power, which means the quadratic increase of mass.

(2) There is an appropriate tether length for the system by the trade off between the increase of performance and the increase of possibility of impact of debris with the increase of tether length.

(3) The increase of number of tether is not necessarily effective for the system by considering the increase of possibility of impact of debris although the system mass decreases with the increase of number of tether.

(4) The system performance is much influenced by the mass flow rate of plasma contactor. The contactor of tether system should operate at larger flow rate where the voltage drop at contactor is not high.

(5) The electrodynamic tether orbit transfer system is advantageous compared with the ion thruster orbit transfer system for the same missions.

**References**


