Identification of the Orbital Tether System Parameters for Small Subsatellites Deorbiting

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Abstract: Flat model of orbital tether system (OTS) with imponderable tether was utilized in this paper. Relay control law was proposed for OTS nominal deployment control. Obtained results afford to choose optimal nominal deployment and control parameters of the OTS for a variety of mother satellite orbits.

Keywords: orbital tether system, control law

1. INTRODUCTION

Orbital tether systems (OTS) are among possible ways of efficiency upgrading of both already constructed and still being developed space engineering. It can be widely used for space maneuvers and special logistic space missions.

Orbital tether system is considered as a cluster of mother satellite (MS) on low earth orbit and subsatellite (payload, descent vehicle) attached to the MS via tether.

One of the practical importance problems is applying OTS to reentry of goods from low earth orbit to Earth. For example, utilization of OTS looks extremely useful in terms of payloads deorbiting from International Space Station (ISS). It can expand largely the ISS's possibilities to near real-time delivery of scientific experimentations results or goods produced in space, like superfine materials and supplies etc.

Orbital tether system offers properties of redistribution of mechanical power from one satellite to another one via attached to both spacecraft tether. Small subsatellite deorbiting maneuver without any break propulsive device and either control or navigation systems is based on this property of the OTS.

2. MODEL OF MOVEMENT

2.1 Orbital tether system

The following deorbiting design is considered:

1. Actuator (push-rod spring) descent vehicle in the direction of the local vertical

2. Guided motion of tethered payload until maximum deviation from local vertical is achieved

3. Tether is locked in the ejection device. Capsule is performing pendulum motion.

4. Cut of tether when local vertical is reached by the payload. Capsule is performing free motion and then reentry.

This particular orbital tether system design leads to sufficient energy redistribution between mother satellite and descent vehicle and makes payload reentry with preassigned angle.

Relative motion of the inertia centers for mother satellite and capsule is given in spatial polar coordinates in Fig. 1.

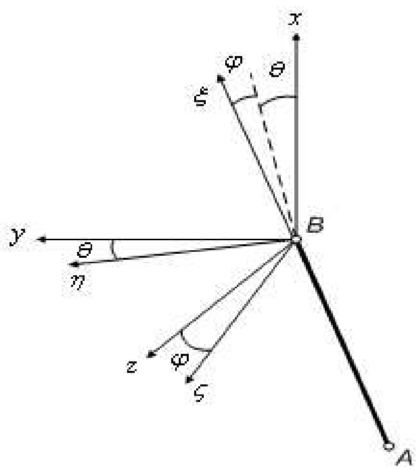

Fig. 1. Orbital tether system in spatial polar coordinates

Fig. 1 contains:

B - center of inertia of mother satellite,

A – mother satellite tether mounting point,

Bx axis is following earth centered position vector, By axis is transversal and Bz is binormal to mother satellite orbit;

θ is steering angle in mother satellite orbital plane ; φ is deviation from the orbital plane angle.

Following dynamic model (equation of motion) is used (Beletsky, 1990)

$$\begin{aligned}
&\dot{\theta} = V_\theta,\\
&\dot{V}_\theta = -\frac{2(V_\theta+\omega)V_r}{r} - 3\omega^2 k^{-1}\sin\theta\cos\theta;\\
&\dot{r} = V_r;\\
&\dot{V}_r = r\left[(V_\theta+\omega)^2 + \omega^2 k^{-1}\left(3\cos^2\theta - 1\right)\right] - \frac{T}{m_A};\\
&\omega = \dot{\nu} = \mu^{1/2} p^{-3/2} k^2,
\end{aligned} \qquad (1)$$

where time differentiation is denoted by dot; $k = 1 + e\cos\upsilon$; e, p and ν are mother satellite B eccentricity, latus rectum and true anomaly; T is tether tension; r is emitted tether length; m_A is subsatellite mass; the following notation is also introduced $\dot{\theta} = V_\theta,\ \dot{V}_\theta = \ddot{\theta},\ \dot{r} = V_r,\ \dot{V}_r = \ddot{r}$.

2.2 Model of restrictions

The model is assuming:

1. the center of inertia of system has undisturbed orbit;
2. the center of inertia of system equals to the center of inertia of mother satellite;
3. the tether is imponderable and approximated as straight and stiff thread;
4. only in-plane movement of orbital tether system is considered

2.3 Control algorithm

Tether tension is considered as a control function for the system. Tether system optimal control program is based on maximum deviation from local vertical criteria while maximum tension is limited. It includes 2 intervals: minimum tension interval (initial phase of second stage) and maximum tension interval (final phase of second stage) as it is shown in the thesis Naumov (2006).

The following tether control law is proposed:

$$T = T_1\left(\frac{1 + sign(r_n - r)}{2}\right) + T_2\left(\frac{1 + sign(r - r_n)}{2}\right), \qquad (2)$$

$r \geq r_{K_1}^{\min}$ is total tether length;

r_n is tether length where T_1 shifts to T_2;

$T_1 > T_{конс}$ is initial tether tension (known beforehand tension of reeling device);

T_2 is maximum tension after shift (during final phase of second stage).

The proposed control law can be implemented and parameterized easily. Main problem of this paper is to choose orbital tether system and control parameters providing desired conditions of the capsule reentry. Numeric solutions were being found for parametric boundary value problem (1) for control law (2). The following boundary conditions were used (index H for initial conditions, index K – for final ones):

$$t = 0,\ \theta_H = 0,\ r = r_{0_2},\ V_{r_H} = 0,\ V_{\theta_H} = 0,$$
$$t = t_K,\ r = r_{K_2},\ V_{r_K} = 0, V_{\theta_K} = 0.$$

Value θ_K was unfixed. Tether tension after shift and tether length before shift were used as parameters. Values V_{r_K} and V_{θ_K} were the boundary residuals.

3. ATMOSPHERE ENTRANCE

Descent vehicle is under heavy heat strain during the reentry. Reasonable accuracy of landing should also be achieved. Acceptable range of reentry angles for small capsules is minus 1,3 – minus 1,8 degree (Siharulkidze, 1982). This paper considers problem of achieving reentry angle value equals to minus 1,5 degree for successful landing of the payload.

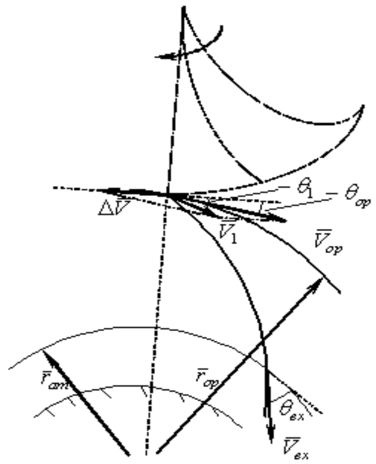

Fig. 2. Determining of reentry parameters

Fig. 2 presents vector $\Delta\overline{V}$ of velocity. Pendulum motion of tethered sub-satellite around center of inertia of system results in this velocity. Resultant velocity after tether cut can be defined from the formula (Siharulkidze, 1982):

$$V_1 = \sqrt{V_{op}^2 + \Delta V^2 - 2V_{op}\Delta V\cos(-\theta_{op})}\,.$$

By some assumptions and one can define formulas for reentry velocity $V_{вх}$ and angle $\theta_{вх}$ from energy and area integrals:

$$V_{вх} = \sqrt{V_1^2 + 2\mu\left(\frac{1}{R_{вх}} - \frac{1}{R_{op}}\right)} \qquad (3)$$

and

$$\theta_{вх} = \arccos\frac{V_1 R_{op}\cos\theta_1}{V_{вх}R_{вх}}\,. \qquad (4)$$

θ_1 is flight-path elevation and can be calculated from simplified formula $\theta_1 = \theta_{op} - \frac{\Delta V}{V_{op}}\sin(-\theta_{op})$.

4. SIMULATION OF ATMOSPHERE ENTRANCE

Satellite movements towards circular orbit simulations were carried-out. In Fig. 3 one can see reentry angle $\theta_{вх}$ versus tether total length for orbital altitudes of 250, 300 and 400 km. Fig. 4 presents reentry angle $\theta_{вх}$ versus maximum tether tension for orbital altitudes of 250, 268 and 500 km. Following results for total tether lengths were collected for low-altitude satellites and reentry angles minus 1,5 – minus 1,51 degree.

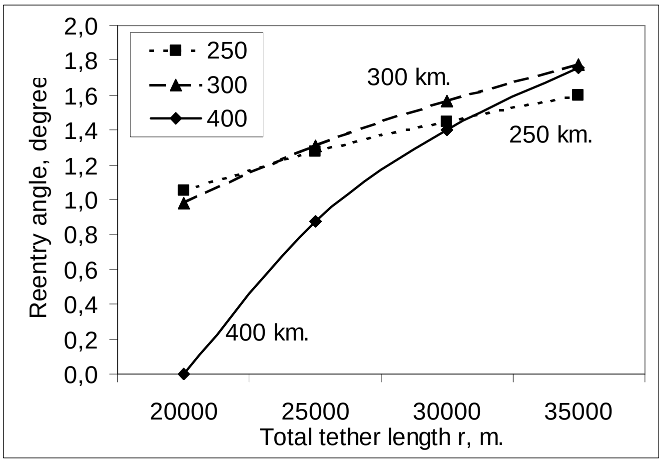

Fig. 3. Reentry angle $\theta_{вх}$ versus tether total length for different orbital altitudes

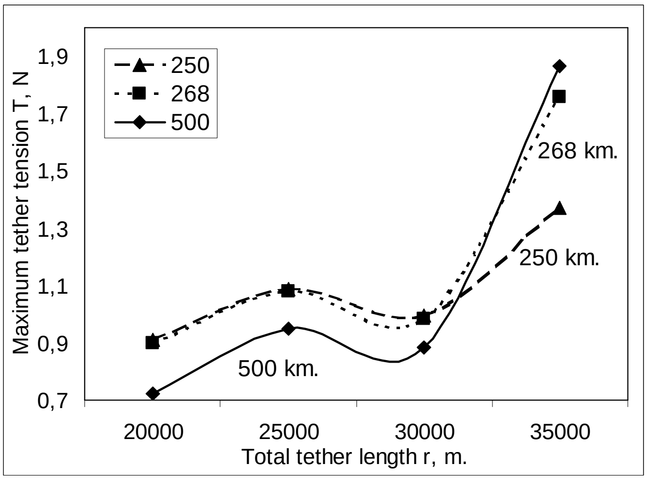

Fig. 4. Maximum tether tension T versus tether total length for different orbital altitudes

Table 1. Circular orbit results

Orbital tether system parameters		Parametric boundary value problem solution		Reentry specification	
Total tether length r m.	orbital altitude R_{op} km.	Tether length where T_1 shifts to T_2; r_n, m.	Maximum tension after shift T_2, N	Reentry angle $\theta_{вх}$, degree	Reentry velocity $V_{вх}$, km/sec.
32000	**250**	25 500	1,00050	**-1,51100**	7,7793
30000	**268**	23 937	0,98435	**-1,50730**	7,7986
29000	**300**	22 993	0,94242	**-1,51800**	7,8221
29500	**350**	22 416	0,82293	**-1,51630**	7,8502
31200	**400**	26 034	1,10370	**-1,50070**	7,8731
36900	**500**	34 750	3,12620	**-1,50360**	7,9096

1. One can see from the Table 1 that reentry angle $\theta_{вх}$ versus total tether length occurs nonlinear.
2. Obtained results allow us to choose total tether length and nominal control parameters for any orbital altitude in the examined range (200-550 km).

5. ELLIPTICAL ORBIT

Circular orbit mother satellite motion dynamic model was utilized in the previous section. The problem of this section was to simulate orbital tether system deployment while mother satellite is moving towards elliptical orbit. New parameters were added to dynamic model (equations of motion) to simulate elliptical orbital motion of OTS. Eccentricity (apogee and perigee) and true anomaly of mother satellite were these parameters were.

Satellite movement towards elliptical orbit simulation was carried-out. Elliptical orbits were chosen to correspond to circular orbits studied in the previous section of the paper. Essentially shorter total tether length (20000 meters) was examined with these orbits.

The ISS's elliptical orbit (382*400 km) was also examined with different total tether length. Mother satellite true anomaly was chosen to reach sufficient reentry angle for various elliptic orbits during the simulation. One can see reentry angle $\theta_{вх}$ versus mother satellite true anomaly ν for total tether length equals 20 km and elliptic orbits with apogee equals 350 km and perigee equals 160, 197 and 250 km on picture 5 and reentry angle $\theta_{вх}$ versus mother satellite true anomaly ν for elliptic orbit with apogee equals 400 km and perigee equals 382 km (ISS) and tether total length equals 20000, 25000 and 30000 meters.

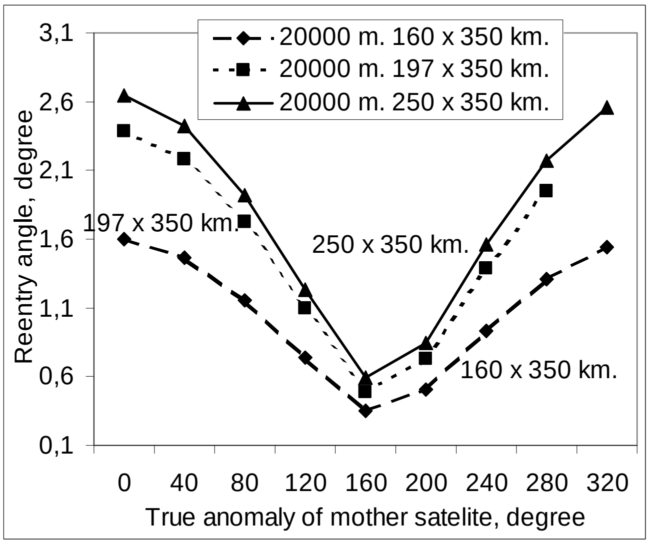

Fig. 5. Reentry angle $\theta_{вх}$ versus true anomaly of mother satellite ν for different elliptic orbits with apogee equals 350 km and total tether length equals 20 km

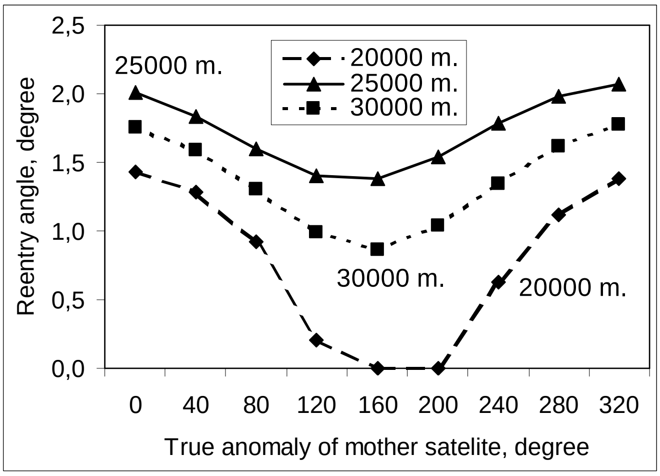

Fig. 6. Reentry angle $\theta_{вх}$ versus true anomaly of mother satellite ν for elliptic orbit with apogee equals 400 km and perigee equals 382 km (ISS) and different tether total length

Following results were obtained:

1. The elliptical orbital movement features can explain low reentry angle for true anomaly angles near 160-180 degrees. Another reason is total tether deployment duration and mother satellite half of orbit passing duration propinquity.

2. Initial deployment stage presence (sub-satellite is "freezing" in the direction of the local vertical) in this paper's problem definition allows true anomaly to reach the sufficient value (by means of start of deployment time). Also system can operate with shorter tether that can simplify the development and makes whole system cheaper.

Table 2. Elliptic orbit results

Orbital tether system parameters				Parametric boundary value problem solution		Reentry specification	
Total tether length r m.	Perigee, km.	Apogee, km.	True anomaly of MS ν, degree	Tether length where T_1 shifts to T_2; r_n, m.	Maximum tension after shift T_2, N	Reentry angle $\theta_{вх}$, degree	Reentry velocity $V_{вх}$, km/sec.
20000	219	**250**	**10**	15 997	0,91398	**-1,51420**	7,7485
20000	247	**268**	**0**	15 989	0,90370	**-1,51450**	7,7844
20000	262	**300**	**75**	16 000	0,89153	**-1,51830**	7,7982
20000	197	**350**	**94**	16 000	0,87668	**-1,51560**	7,7012
20000	225	**400**	**110**	15 500	0,76963	**-1,50380**	7,7590

6. CONCLUSIONS

Results have shown us that time as a parameter should be added to the deployment model subsequently. Landing zone of payload should also been taken into consideration for the model to be applied to real space missions. Nevertheless simulation has shown that control and orbital tether system parameters (true anomaly, total tether length) can be chosen for low orbit satellite to satisfy required reentry conditions (reentry angle between minus 1,3 – minus 1,8 degrees) in nominal conditions mode.

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