Strategy for the realization soft docking with space debris by using tether system

R.S. Pikalov[1]

[1]Samara National Research University, Moskovskoe Shosse 34A, Samara, Russia, 443086

Abstract. This study focuses on a dynamics of a rendezvous of a tug and large space debris connected by a viscoelastic tether. It is assumed that a control is realized by changing the length of the tether. The goal is to study the dynamic of the maneuver of the rendezvous and to find the ways, which allow one to reduce the oscillation of the tether. The obtained results can be applied as applications for the tasks of implement rendezvous of two bodies using the tether.

1. Introduction

In the near future space debris can put an end to further space exploration [1-3]. Today, there are more than 15,000 large objects on the orbits around the Earth. All these objects are tracked. An active spacecraft or a space station can avoid collision with such objects [3-5]. Collisions of the space debris with spacecraft and other debris can significantly increase numbers of the small debris on the Earth orbit and can cause by the Kessler syndrome [1, 2]. There is a large number of papers devoted to this problem [3-26]. Different approaches have been were offered to removal the defunct satellites and the old upper stages [3, 6-11]. These approaches can include the use of the tether systems [3, 5, 12]. The tether can be used as a means of the soft docking of the active spacecraft (space tug) and the defunct satellites or the old upper stages (space debris) [8]. In this case the space tug and the space debris are pulled together using the tether.

This study focused on the stages of the rendezvous and the soft docking the space debris with the space tug. In the works [20-22] it was found that as a result of the rendezvous there is a rotation of system, around its own center of mass. And the speed of rotation increases as the space debrisapproach to the tug. The goal of this work is to study the mechanism of occurrence of this phenomenon and to develop ways to eliminate it.

2. Motion equations

To study the optimal means for controlling the angular motion of system to minimize the librations of the ribbon, a simplified model of the system is used. In this work we investigate the motion of the space tether system consisting of a space tug and tethered space debris.

The space tether system is presented in figure 1. The figure shows the space tug (m_1), space debris m_2 and elastic tether. The space tug and the space debris are considered as mass points with masses m_1 and m_2 respectively. We assume that the our system of the considered in non gravitational field. We assume that the thrust tug $\mathbf{F}$ coincides with the coordinates vector x.

The origin of the frame coincides with the center of mass of system - point C. The coordinate axes x is in direction of the tangent to the orbit in point C, axes y is in the direction from the Earth`s center to point C. As generalized coordinates we chose l is a distance between the tug and space debris and angle α which define the rotation of system around own center mass.

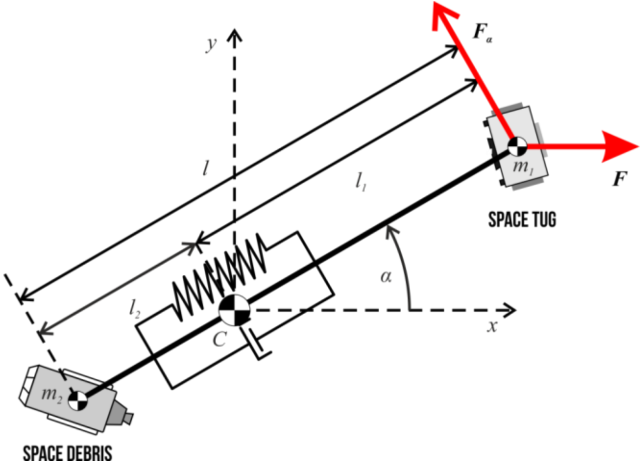

Figure 1. Scheme of the system.

Let the position of the space tug and the space debris be written in the coordinate frame

$$\mathbf{r}_1 = l_1\begin{pmatrix}\cos\alpha\\ \sin\alpha\end{pmatrix} \tag{1}$$

$$\mathbf{r}_2 = l_2\begin{pmatrix}\cos\alpha\\ \sin\alpha\end{pmatrix} \tag{2}$$

where l_1 and l_2 are defined as

$$l_1 = l\frac{m_2}{m_1+m_2},\quad l_2 = l\frac{m_1}{m_1+m_2} \tag{3}$$

where m_1 and m_2 are masses of the tug and the space debris respectively.
Substituting (3) in (1) - (2) we obtain

$$V_1^2 = \left(\frac{m_2}{m_1+m_2}\right)\left(\dot{l}^2 + l^2\dot{\alpha}^2\right),\quad V_2^2 = \left(\frac{m_1}{m_1+m_2}\right)\left(\dot{l}^2 + l^2\dot{\alpha}^2\right)$$

The total kinetic energy of the system is calculated by

$$T = \frac{1}{2}\frac{m_1m_2}{m_1+m_2}\left(\dot{l}^2 + l^2\dot{\alpha}^2\right) \tag{4}$$

The potential energy of the system is calculated by

$$\Pi = H[l]\frac{c}{2}(l-l_0)^2 \tag{5}$$

where $H[l]$ is the Heaviside function [27] define as

$$H[l] = \begin{cases}1, & l > l_0\\ 0, & l \le l_0\end{cases} \tag{6}$$

After application of Lagrange's equations, the equations of motion are given by

$$\begin{cases}\dfrac{m_1m_2}{m_1+m_2}\ddot{l} - \dfrac{m_1m_2}{m_1+m_2}l\dot{\alpha}^2 + H[l]c(l-l_0) = Q_l\\[2ex] \dfrac{m_1m_2}{m_1+m_2}l^2\ddot{\alpha} + 2\dfrac{m_1m_2}{m_1+m_2}l\dot{l}\dot{\alpha} = Q_\alpha\end{cases} \tag{7}$$

Next, we define the generalized force in Lagrange's equation (7)

$$Q_l = F\cos\alpha + H[l]k_d\left(\dot{l} - \dot{l}_0\right) \tag{8}$$

where in first term respond for the thrust of the tug, second term for the damping force. The damping forces in the tether play an important role for reducing the effects of longitudinal vibrations, as well as for helping to improve numerical stability.

$$Q_\alpha = F\sin\alpha - F_\alpha l_1 \tag{9}$$

where in the first term respond for the thrust of the tug, second – for the force of control of angle α which define as

$$F_\alpha = k\dot{\alpha}$$

where k is a damping coefficient.

Substituting (8) and (9) in (7) we obtain

$$\begin{cases} \ddot{l} - l\dot{\alpha}^2 + H[l]c(l - l_0) = F\cos\alpha + H[l]k_d(\dot{l} - \dot{l}_0) \\ \ddot{\alpha} + \dfrac{2}{l}\dot{l}\dot{\alpha} = -\dfrac{1}{m_2 l}k\dot{\alpha} + \dfrac{F}{Ml}\sin\alpha \end{cases} \tag{10}$$

where $M = m_1 m_2/(m_1 + m_2)$ is the reduced mass of the system.

We derivate the length control law [20]

$$l_0 = \frac{L_0}{2}(1 + \cos\varphi t) \tag{11}$$

where $\varphi = \pi/t_k$, t_k is the duration of the maneuver, L_0 is an initial length of the tether. The expression (11) satisfies the requirement that

$$l_0(t_k) = 0$$

If the tether is rigid then the velocity of the space debris relative to the space tug will be equal to zero.

3. Conclusion

We developed mathematical model the space tether system consisting of a space tug and tethered space debris. In further research, using the obtained model, the mechanism of the system spin around its own center of mass will be investigated and ways to avoidance this.

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