APPLICATION OF SPACE TETHERED SYSTEMS FOR SPACE DEBRIS REMOVAL

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Abstract

Implementation of space tethered systems is an interesting and important scientific and technical problem. Tethered systems may be used for a wide range of purposes, for example, to execute orbital maneuvers , to establish "orbit-mail", to clean up space debris and for many other purposes while almost no fuel is required. This paper deals with an application of space tether systems for cleaning of elements of space debris or another unwanted waste from orbits or space stations [1].

We consider a space tethered system which consists of a “big” satellite with a counterweight mass (“small” satellite) attached to it by means of a flexible tether. The system moves in the gravitational field along a circular Earth orbit. A small load (a container) can move (transport) along the tether in the direction from the “big” satellite to the “small” one. Loads are opening capsules with space debris elements or other objects inside. When a load reaches the “small” satellite it stops and special devices can measure change of mass. With the accumulation of a certain critical mass (few loads) at the end of the tether, the collected loads are released and can move to a lower orbit where they will not be dangerous for active space missions or they will burn up on entering the Earth's atmosphere.

We propose to arrange a counterweight as follows. It consists of a few loads that are fastened together with a special device. This device is a tripod with elastic “legs”. If the collected mass less than a certain value the legs are unfolded (Fig .1(a)). At a certain number of collected containers at the counterweight when new coming load impacts the upper container, under this impact the “legs” fold and the lower container can be released. It starts moving. The initial speed is determined by the impact that transmits from the incoming load (Fig. 1(b)). The limit of collected mass and the mass ratio between the lads and the counterweight is determined by the elastic material properties of the “legs”. After releasing the load, the “legs” return to the unfolded position (Fig.1 (c)).

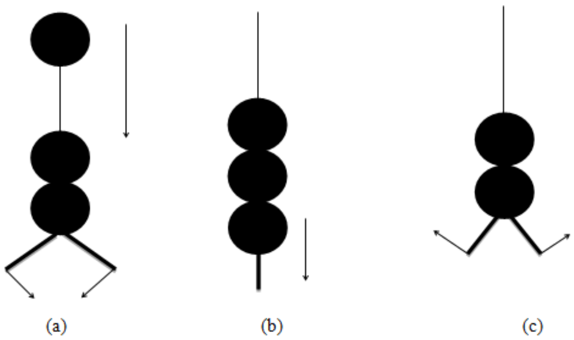

Figure 1.The principle scheme of device of loads collection and releasing.

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At certain relationships between masses of the load and counterweight the velocities of containers and counterweight can be small and their motion is stable and it can be considered as quazistatic. In this case the influence of dynamic effects in the tether is negligible in compare with the influence of mass forces (Coriolis force, inertial forces, Earth's gravity). In this approach we consider the problem of stable loads transporting along the tether.

This problem was set and solved. The numerical results confirmed analytical conclusions and show the strong dependence of stability of motion of loads along the tether on the relation between the masses and initial velocity of a load.

1. **Mathematical statement of the problem.**

Let us assume that a "big" satellite moves along a circular orbit of radius R with constant angular velocity ω. Then it releases a "small" satellite with mass M at its end. The coordinate system is connected with the "big" satellite. At the initial time we assume that the system is stabilized as it shown in [2].

Let us direct the OX axis towards the Earth and the OY axis along the trajectory of the "big" satellite. In this system of coordinates external forces include the force of gravitational attraction to the Earth, the centrifugal force and the Coriolis force. In this paper we consider that the tether is not electrically conductive, so, the forces of electromagnetic interaction are missed. The total Lagrange length of the tethers L.

S is a Lagrange coordinate of an element of the tether.

$x(s,t)$, $y(s,t)$ are displacements in OX and OY directions respectively.

$X(s,t)$ and $Y(s,t)$ area Cartesian coordinates of a particle of a part of the tether (Fig.1).Point $X(s,t) = X(0,t) = 0$ is the point where the tether leaves the "big" satellite.

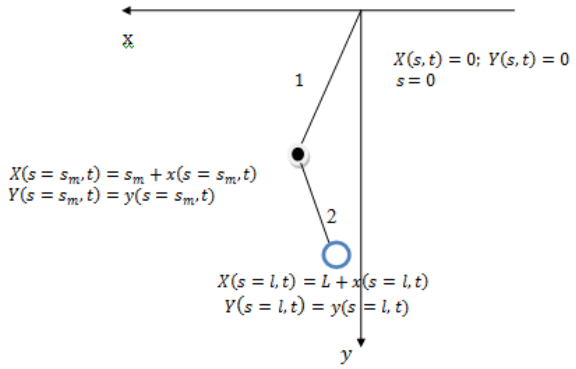

Figure.2.Choice of the coordinate system.

We got equations of motion of deformable strings from [3]. In case when the tethered system moves along a circular orbit these equations can be written in the following way [4]:

$$\begin{cases} \rho(\frac{\partial^2 x}{\partial t^2})_i = \frac{\partial}{\partial s}(T\cos\gamma)_i - 2\omega\rho(\frac{\partial y}{\partial t})_i + 3\omega^2\rho(s+x) \\ \rho(\frac{\partial^2 y}{\partial t^2})_i = \frac{\partial}{\partial s}(T\sin\gamma)_i + 2\omega\rho(\frac{\partial x}{\partial t})_i \end{cases}$$

Here ρ is the density of the tether, T is tension γ is an angle deforming part of tether and OX axis. Index i represents parts of the tether before or after the load (1 or 2).

We can express the deformation of the element as:

$$\varepsilon_i = \sqrt{(1+x_i)^2 + y_i{}^2} - 1$$

And for cosines and sinus we have the following formulas:

$$\cos\gamma = \frac{1+(\frac{\partial x}{\partial s})_i}{1+\varepsilon_i};\sin\gamma = \frac{(\frac{\partial y}{\partial s})_i}{1+\varepsilon_i}.$$

Dependence of tension on relative deformation is considered as a linear function:

$$T_i = E\varepsilon_i$$

Where E is Young's modulus – constant of material.

At the point $s = s_m$, Cartesian coordinates $x_m(s_m,t), y_m(s_m,t)$ of attachment to the load we have such dynamic boundary conditions for connecting two parts of tether:

$$\begin{cases} \rho\frac{d^2x_m}{\partial t^2} = -T_1\cos\gamma_1 + T_2\cos\gamma_2 - 2\omega m\frac{dy_m}{dt} + 3\omega^2 m(s_m + x_m) \\ \rho\frac{d^2y_m}{dt^2} = -T_1\sin\gamma_1 - T_2\sin\gamma_2 + 2\omega m\frac{dx_m}{dt} \end{cases}$$

At the point $s = L$ of attachment to the "small" satellite with mass M we have such dynamic boundary conditions:

$$\begin{cases} m\frac{d^2x_L}{dt^2} = -T_L\cos\gamma_L - 2m\omega\frac{dy_L}{dt} + 3m\omega^2(L + x_L) \\ m\frac{d^2y_L}{dt^2} = -T_L\sin\gamma_L + 2m\omega\frac{dx_L}{dt} \end{cases}$$

And initial conditions are considered as follows

$$x(s,0) = 0; \frac{dx}{dt}(0,0) = V_0$$

$$y(s,0) = 0; \frac{dy}{dt}(0,0) = 0$$

2. Numerical calculations

The analysis shows that the behavior of the system is highly dependent on the mass ratio and initial speed of load. Trajectories of loads at different masses ratios shown in Figure 2.Trajectories of "small" satellite at different masses ratios shown in Figure 3. We take ω= 0.00011 rad/s (angle velocity in the GEO), M =14 kg, l =30000 m as parameters of the system. And initial speed of the load is 2 m/s. Curve 1 corresponds to the mass ratio of loads and "small" satellites 1:10, curve 2 corresponds to mass ratio 1:5 and curve 3 is to 1:1 (Figure 2). Curve 4 corresponds to the mass ratio 1:10, curve 5 corresponds to 1:5 and curve is to 6 – 1:1 accordingly (Figure 3).

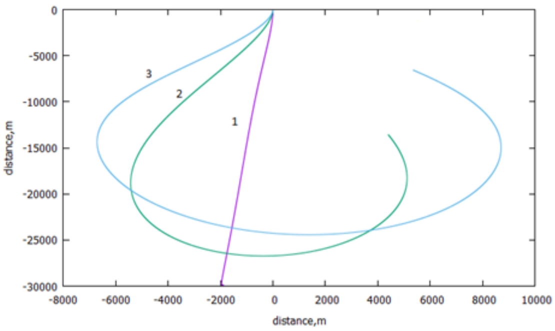

Figure.3. Trajectories of loads at different masses ratios

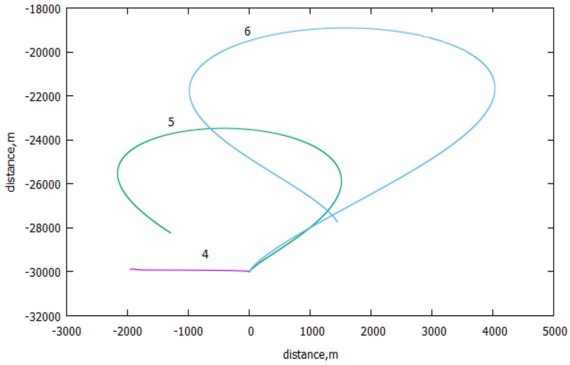

Figure.4.Trajectories of "small" satellite at different masses ratios

As we can see in Figures 2 and 3, the most realistic conditions for stable and controllable transportation of loads when the masses ratio is 1:10 and more (curves 1 and 4). Also in this case the assumptions about smallness of velocities and deformations in tether are performed. In the other cases we can see strong deviations of the tether from the local vertical and large displacements of a "small" satellite. In the condition of real space operation it means the failure of the mission.

Figure 4 shows the trajectory of a load (container) at different initial velocities. It can be seen that by increasing the initial velocity (curve 7 corresponds initial speed of 4 m/s and curve 8 – 5 m/s) there is a large displacement of the load, there are loops of trajectory. In the condition of the real space operation it also means the failure of mission.

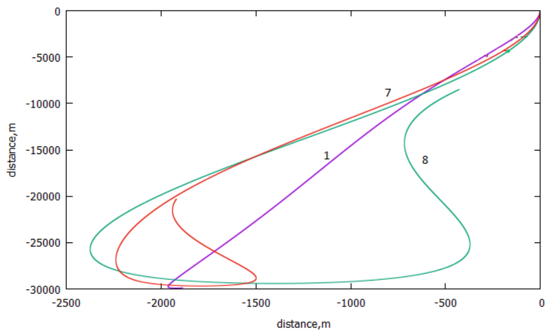

Figure.5.The trajectory of loads at different initial velocities

We can conclude that the most realistic conditions for stable are the ratio of masses 1:10 and initial loads speed 2 m/s. All subsequent calculations were performed with these parameters.

It should be mentioned that the movement of the tether in the system is directly dependent on velocity of transverse waves in tether. It is important that the velocity of the transverse waves in the tether must be greater than the speed of movement of the load along the tether. Otherwise, undesirable overlaps of the tether and the load can occur. Fig. 5 shows that at mass ratio 1:10 and initial velocity of the load 2 m/s the velocity of transverse waves (curve 10) is greater than the velocity of loads (curve 9). A small increase in wave velocity indicates small relative deformations in the tether.

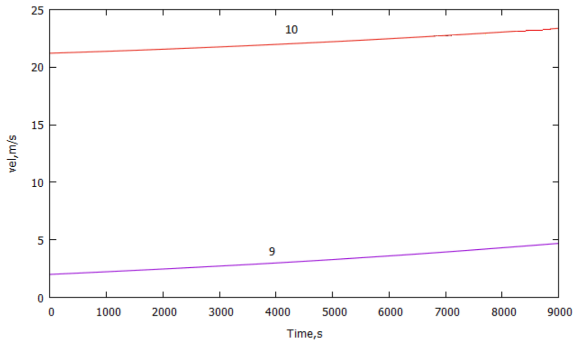

Figure.6. Velocities of loads descent (9) and transverse waves(10)

3. Conclusions

A certain scheme is proposed for transportation of loads from one orbit to another with the help of a space tether system. The analysis shows strong dependence of transverse displacements of a load on its mass, initial speed and the mass of counterweight. . In space such deviations can play a major role in the loads movement and subsequently stabilization of the whole system. It is necessary to chose carefully the parameters of system (mass of the load, initial velocity of the load, mass of the "small" satellite). One solution of the problem is proposed based on the results of numerical calculations.

References.

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