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Dynamic control of the space tethered system

A.A. Malashin [a,*], N.N. Smirnov [a], O.Yu. Bryukvina [b], P.A. Dyakov [a]

[a] *Lomonosov Moscow State University (MSU), Faculty of Mechanics and Mathematics, Main Building, GSP-1, 1 Leninskiye Gory, Moscow 119991, Russia*
[b] *Moscow State Forest University (MSFU), Mytishchi, Moscow Region 141005, Russia*

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ABSTRACT

We discuss the problem of simultaneous dynamical stabilization and suppression of transverse and longitudinal vibrations of the space tethered system deployed along a certain trajectory. The dynamics of the system is described by a system of nonlinear partial differential equations for the longitudinal and transverse waves and we consider a non-classical version of the problem with one moving boundary. We formulate a mathematical model and perform the analytic and numerical analysis of the boundary control problem based on the Lyapunov method. A scheme of the deployment mechanism is suggested. It includes a control torque and transverse displacement of the boundary and ensures stable deployment of the whole system.

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1. Introduction

Implementation of the space tethered systems is an interesting and important scientific and technical problem [1–3]. The tethered systems have a wide range of applications. For example, they can be used to perform orbital maneuvers [4–9], to establish "orbit-mail" [10], to clean up space debris [11–14] and for many other purposes while almost no fuel is required. Some challenges to the real use of the space tethered systems are presented in [15–19]. The vibration processes in the tethers due to complicated dynamics and some means to control the motion of the tethered systems are studied in [20–25].

Dynamic control of the tethered systems becomes quite a difficult technical problem even at the deployment stage. One of the challenges arising during the deployment and further stabilization along a certain trajectory is appearance of undesired transverse and longitudinal vibrations of the tether. These vibrations make the deployment process difficult to control. It is of a special importance for the systems with long tethers. Most of the calculations related to the tethered systems are based on the quasi-static approximation. Thus, longitudinal fluctuations of the tether are missed. In some studies the tether is considered as a set of masses connected by elastic links. In general, these approaches are good. At low speed of the deployment along a smooth trajectory the behavior of the system can indeed be considered as quasi-static [26]. However at the initial and the final stages of the deployment process, as well as in the case of possible perturbations caused by interaction with the micrometeorites or particles of space debris or by any technical problem of the deployment mechanism, the longitudinal and transverse vibrations of the tether must be taken into account [26].

The generation of undesired transverse and longitudinal vibrations becomes crucial for the systems with long tethers. The YES2 project [4,5] designed to move a small satellite to a lower orbit gives a real life example of such a phenomenon. In

* Corresponding author.
E-mail address: malashin_a@mail.ru (A.A. Malashin).

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this experiment a small satellite "Fotino" was launched from a big satellite "Foton" towards the Earth at a non-zero initial velocity. The total length of the deploying tether was about 32 km. At the end of the deployment process the satellite speed exceeded the expected value, the tether experienced longitudinal vibrations of an enormous amplitude and the satellite has been lost. According to Ref. [26] the trajectory of the small satellite and motion of the tether is very unstable with respect to even tiny variations of the initial velocity and mass of the small satellite and the tether tension. Moreover, in the case of a periodic regime with a given frequency at the boundary required to deploy the tether, various resonance phenomena always occur in the tether and lead to unlimited increase of the amplitude of transverse and longitudinal waves [27]. All these effects cannot be properly taken into account within the quasi-static approximation and require the dynamical analysis based on the partial derivative equations (PDEs).

In the present paper we consider such a space tethered system which consists of a big and a small satellite connected by a flexible tether. The system moves in the gravitational field along the circular orbit. Unwinding or winding of the tether moves the small satellite away from or towards the big one. The tether's speed can be managed by equipment installed on the big satellite.

For this system we formulate and solve the problem of the boundary control of three-dimensional transverse and longitudinal vibrations of the tether with the increasing length. The dynamics of the flexible and stretchable tether is described by a system of non-linear PDEs. We observe that the vibrations of the tether with one moving endpoint may be controlled by changing the tether tension and the angle of deviation from the given trajectory at the opposite endpoint. In the paper we identified conditions of the simultaneous boundary control over the deployment of the system.

2. The mathematical setup of the problem

Let us assume that a big satellite moves along a circular orbit of radius R with the constant angular velocity ω. Then it releases a tether with a small satellite of the mass m at its end. In this example we assume that the small satellite is moving towards the Earth and that the coordinate system is connected with the big satellite.

Let us direct the OX axis towards the Earth and the OY axis – along the trajectory of the big satellite, while the OZ axis is perpendicular to the plane of the orbit. In this coordinate system the total external force is a sum of gravitational attraction to the Earth, the centrifugal force and the Coriolis force. In this paper we consider a nonconductive tether and neglect its electromagnetic interaction. The following notations are adopted:

L is the total Lagrange length of the nonstretched tether;

s is the Lagrange coordinate of an element of the tether. $x(s,t)$, $y(s,t)z(s,t)$ are the displacements along OX, OY and OZ axis respectively; $\ell(t)$ is the Lagrange length of the unwound part of the tether; $X(s,t)$ is the Cartesian coordinate of a particle of the free part of the tether (see Fig. 1). We get the expression $X(s,t) = s + x(s,t) - \ell(t)$. The tether leaves the big satellite at the point $X(s,t) = X(\ell(t),t) = 0$.

The time dependence of $\ell(t)$ can be represented as follows:

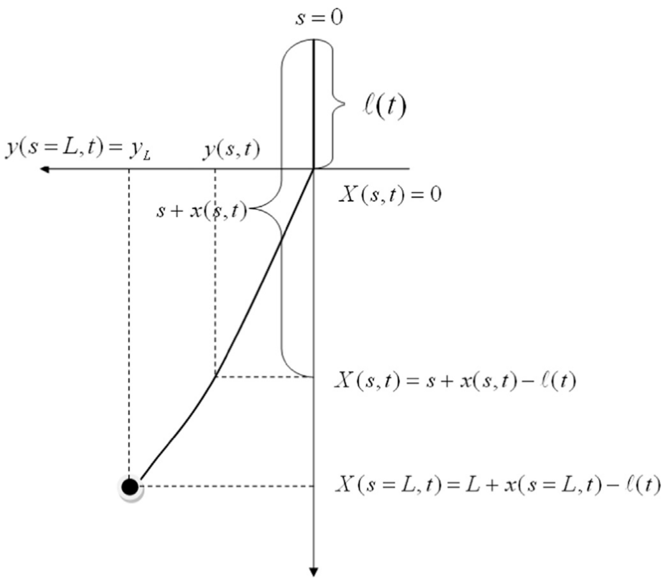

Fig. 1. The model of the tether's deployment. The point $X(s,t) = 0$ $y(s,t) = 0$ remains at the big satellite. The part of the tether $\ell(t)$ is placed on the spinner at the big satellite.

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