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Ground-based experiments of tether deployment subject to an analytical control law

B.S. Yu, L.L. Geng, H. Wen, T. Chen, D.P. Jin*

State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, 210016, Nanjing, People's Republic of China

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ABSTRACT

Tethered satellite systems (TSSs) have shown great application potential in space missions, such as debris capture, active debris removal, and tether assisted observation. When the tether is deployed on-orbit, it may undergo a taut-slack process. This makes controlling a tether deployment more difficult than controlling a suspended tether. This paper examines a tether deployment subjected to an analytical control law in a ground-based experimental testbed. A dynamics similarity is proposed for the ground-based experiment to reproduce the dynamic environment of the tether deployment of the on-orbit TSS. Gravity compensation is used in the experiment to balance the friction forces and gravitation components that arise from the slight inclination of the testbed. The controlled stability is evaluated by the convergence of the pitch motion of the tether. The experimental results show that the controlled tether is successfully deployed along an assigned direction under a taut state during the deployment phase.

1. Introduction

Deployment control of the tether from a mother satellite plays an important role in operations during a TSS mission [1–5]. The stability of tether control methods can be verified by using various technologies, including numerical simulations, ground-based experiments, and on-orbit flights. Compared to numerical simulations and on-orbit flights, the ground-based experiment of TSS is more useful for the verification of dynamics control [6–10].

Tether deployment control has drawn much attention for decades. Here are a few, but typical examples. Targeting control strategy for deployment of a TSS on circular orbit is investigated by Barkow et al. [11]. Based on tether-length rate control, the deployment of multi-connected satellites aligned along the local horizontal is numerically studied by Kumar et al. [12]. With the aid of thrusters, the tether deployment of an electrodynamic tether system from a spool-type reel is performed by Iki et al. [13], where the thrusters are used to ensure the deployment of a multi-kilometer tether. To suppress the in-plane oscillations of TSS during deployment/retrieval, the center manifold method is employed by Steindl [14]. Through the use of a proportional-derivative brake control, the thrust-aided deployment operation of a tape-shaped tether of several kilometers from a spacecraft is studied by Mantellato [15]. The deployment control for a tether-assisted return mission of a re-entry capsule is presented by Aslanov [16], wherein a control strategy based on the tether length rate is used to ensure that the deflection angle of the tether from the local vertical increases gradually. The stability of tethered space robots during target capturing is analyzed by Huang et al. [17–19]. These numerical cases show that the oscillation of the deployed space tether is suppressed through robust control strategy.

On the other hand, there has been significant interest in experimentally verifying the dynamics and control of the tethered system. For example, an experiment for the attitude control of a tethered space robot is executed by Nohmi et al. [20], in which a drop shaft is employed to provide a high quality microgravity condition. With the help of the synchronized position hold, engage, and reorient experimental satellites testbed in a ground laboratory, the array spin rate and relative attitude of a tethered formation system is studied by Chung et al. [21]. The quasi-periodic motions of a TSS with a period of two orbits are successfully observed by Kojima et al. [22], who use a slope rotary table to emulate the Earth's gravity. The existence of the quasi-periodic motion of a tethered sub-satellite with attitude is also verified by Jin et al. [23], whose experimental results agree with the numerical simulations. A set of ground experiments on the deployment of an electrodynamic tether is performed by Iki et al. [24], and numerous key parameters are estimated. By using the extended time-delay auto synchronization (ETDAS) approach, a ground experiment of a controlled tethered satellite is designed and developed by Pang et al. [25]. The

* Corresponding author.
E-mail addresses: yu_bensong@nuaa.edu.cn (B.S. Yu), linglu_geng@163.com (L.L. Geng), wenhao@nuaa.edu.cn (H. Wen), chenti@nuaa.edu.cn (T. Chen), jindp@nuaa.edu.cn (D.P. Jin).

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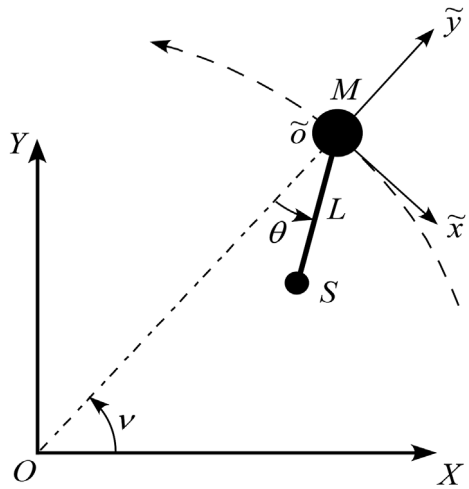

Fig. 1. . A simplified model for on-orbit TSS.

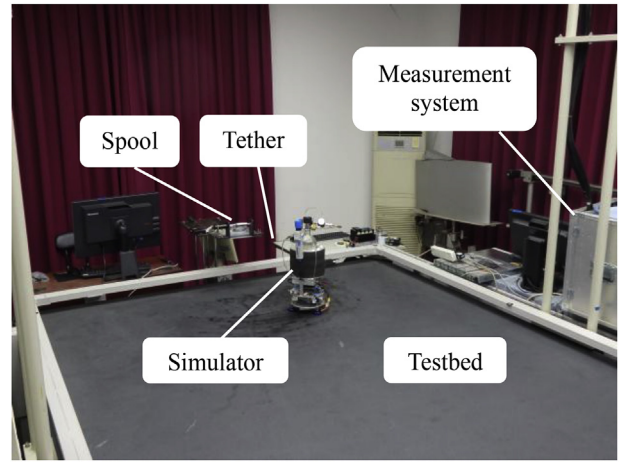

Fig. 2. Ground-based experimental system.

experimental results show that the ETDAS method is capable of stabilizing chaotic motions.

In previous works, most of the control laws of tether deployment have not been experimentally evaluated, and the experiments were focused on the dynamics and control of the tether system during the station-keeping phase. Experiments for tether deployment along an assigned direction are still a tougher problem. The aim of this paper is to experimentally validate the stability of tether deployment governed by an analytical control law, which can ensure tether deployment along a specified direction under a taut state.

The remainder of the paper is organized as follows. An on-orbit model of the tethered satellite and a ground-based model of the tethered system, respectively, are described in Section 2. A tether deployment control law is proposed in Section 3. The experimental system is introduced briefly in Section 4. The numerical simulations and experimental results are presented in Section 5. Finally, the conclusions are drawn in Section 6.

2. Modeling of ON-ORBIT and ground-based tethered systems

As shown in Fig. 1, the in-plane pitch motion of an on-orbit TSS on a Keplerian orbit during deployment is studied. The system consists of a mother satellite M, a sub-satellite S, and a tether of variable length L(t) that connects the two satellites. The mother satellite and sub-satellite are treated as particles. In what follows, it is assumed that the mother satellite mass is much larger than that of the sub-satellite and the space tether is envisioned as a massless rigid rod.

An inertial frame O–XY with an origin at Earth's mass center is presented as shown in Fig. 1. The X-axis of the inertial frame points the direction of the ascending node from origin O, and the Y-axis is perpendicular to the X-axis, and the direction of which is exhibited in Fig. 1. An orbital reference frame $\tilde{o}$–$\tilde{x}\tilde{y}$ is centered at the mother satellite such that the $\tilde{x}$ -axis is in the opposite direction of the motion, and the $\tilde{y}$ -axis points the direction of origin $\tilde{o}$ from the Earth center O. The pitch angle of the system is defined as θ. The orbit's true anomaly is ν.

By a straightforward application of Lagrange's equations, as detailed in Ref. [26], with the generalized coordinate vector $(\theta, L)^{\mathrm{T}}$, the equations of deployment motion of the on-orbit TSS are obtained as follows

$$\begin{cases} L\ddot{\theta} + 2\dot{L}\dot{\theta} = -2\Omega\dot{L} - \dot{\Omega}L - 3\Omega^2 L\sin\theta\cos\theta + Q_\theta/(m_S L) \\ \ddot{L} - L\dot{\theta}^2 = 2\Omega L\dot{\theta} + 3\Omega^2 L\cos^2\theta - \tilde{T}/m_S \end{cases} \tag{1}$$

where the dot represents the derivative with respect to time t, m_S is the mass of the sub-satellite, and $\tilde{T}$ is the tensional force of the tether. $\Omega = \mathrm{d}\nu/\mathrm{d}t$ is the orbital angular velocity of the system. It is evident that Ω is constant when the system runs on a circular orbit. Q_θ denotes the generalized force corresponding to the generalized coordinate θ. Note that Q_θ would equal zero provided environmental perturbations and control torques of the system are ignored.

Setting $\xi = L/L_r$ as the non-dimensional deployed tether length, with L_r being the reference tether length, the non-dimensional transformation can be implemented as follows

$$\frac{\mathrm{d}(\ )}{\mathrm{d}t} = \frac{\mathrm{d}(\ )}{\mathrm{d}\nu}\cdot\frac{\mathrm{d}\nu}{\mathrm{d}t} \tag{2}$$

Then, non-dimensional dynamic equations of motion are given by

$$\begin{cases} \theta'' + 2(\theta' + 1)\left(\frac{\xi'}{\xi} - \frac{e\sin\nu}{\kappa}\right) + \frac{3}{\kappa}\sin\theta\cos\theta = 0 \\ \xi'' - \frac{2e\sin\nu}{\kappa}\xi' - \left[(\theta' + 1)^2 + \frac{3\cos^2\theta - 1}{\kappa}\right]\xi = -u \end{cases} \tag{3}$$

where the prime denotes the derivative with respect to true anomaly ν, e represents the orbit eccentricity of the TSS, $u = \tilde{T}/m_S\dot{\nu}^2 L_r$ is the non-dimensional control variable, and the parameter $\kappa = 1 + e\cos\nu$.

Accordingly, the ground-based experimental system is constructed as shown in Fig. 2. The system consists of a satellite simulator that serves as the sub-satellite, a deployment mechanism, a set of measurement systems, and a testbed. A spool installed on the deployment mechanism is considered the mother satellite, in which the tether is treated as a massless rigid rod. The experiment is detailed in Sec. 4.

The mechanics model of the experimental system is shown in Fig. 3. A ground-based reference frame with the coordinate origin o in the center of the spool is denoted by (x,y), where the x-axis parallel to the border of the testbed and the y-axis is perpendicular to the x-axis. The dynamic equations of the ground-based experimental system are

$$\begin{cases} l\ddot{\theta} + 2\dot{l}\dot{\theta} = F_\theta/m_s \\ \ddot{l} - \dot{\theta}^2 l = (F_l - T)/m_s \end{cases} \tag{4}$$

where l is the tether length, θ is the pitch angle of the system, m_s is the mass of the satellite simulator, and T is the control force. The variables F_θ and F_l represent the Coriolis forces.

To ensure the ground-based experimental system can reproduce the dynamics environment of the on-orbit TSS, the equations of motion must be analogous in the sense of dynamics similarity. Thus, by comparing Eq. (4) with Eq. (1), one obtains

$$\begin{cases} F_\theta = -m_s l(2\omega\,\dot{l}/l + \dot{\omega} + 3\omega^2\sin\theta\cos\theta) \\ F_l = m_s\omega\, l(2\dot{\theta} + 3\omega\cos^2\theta) \end{cases} \tag{5}$$

where ω is the angular velocity of the experimental system. Intuitively, one can make use of this system to gain insight into the dynamics of the