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Modeling and dynamics of a bare tape-shaped tethered satellite system

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ABSTRACT

This paper focuses on the rigid-flexible coupling modeling and dynamics of a bare tape-shaped Tethered Satellite System (TSS). The rigid element is adopted to discretize the tape-shaped tether into a system of rigid bodies with equivalent linear springs and dampers serving as the junctions between the adjacent rigid elements. The equations of motion of the rigid elements are obtained using Newton's second law and the theory of angular momentum. Further, the influence of environmental perturbations on the dynamics of the tape-shaped TSS is investigated, including the atmospheric drag, electrodynamic force, and heating impact. The simulation results show that complicated dynamic phenomena for attitude motions and tether configuration changes will be observed in the tape-shaped bare tethered satellite system.

1. Introduction

A bare thin-cylindrical or tape-shaped tether in space, based on the orbital-motion-limit (OML) theory, can collect electrons [1]. The use of a bare tape-shaped tether to connect two satellites has drawn considerable attention in the past decade [2,3]. Intensive studies have been made on the survivability of tape-shaped tethers in space [4–8], and on the design and experiment of tape-shaped tether deployment systems [9–11]. For instance, a reinforced aluminum tether with a width of 25 mm and thickness of 50 μm was successfully deployed to 132.6 m in the Tether Rocket Experiment (T-Rex) [12,13].

In the above design for the experiments of tape tether system, the bending and torque of the tape tether were ignored [14] and a rigid-rod model was adopted [15]. Clearly, the dynamical model of a tape-shaped tethered system is different from that of a conventional string-tethered system because of the inevitable bending and torque arising from the tape-shaped tether [16]. The numerical and experimental results have been used to predict bending and torsion vibrations in a tape-shaped aluminum tether with a length of 1 m [17]. Additionally, the electrodynamic force that occurs in a bare tether is closely coupled with the flexural deflection of the tether [18]. In other words, a tape-shaped electrodynamic tether (EDT) has more design redundancy in rigidities than a string tether. This paper presents rigid-flexible coupling modeling of a tape-shaped TSS based on discretized rigid elements, with equivalent linear springs and dampers serving as the junctions between the rigid elements and then studies the dynamic responses of the system under environmental perturbations, such as atmospheric drag, the heating effect, and electrodynamic force.

The organization of this paper is as follows. The equations of motion of a tape-shaped tethered satellite system discretized by rigid elements with junctions are established in Section 2, and the equivalent rigidities of the junctions are presented in Section 3. The environmental perturbations, such as the heating effect and electrodynamic force, are given in Section 4. The dynamic responses of the system are investigated numerically in Section 5. Finally, the numerical simulation results are concluded in Section 6.

2. Modeling of tape-shaped tethered satellite

As shown in Fig. 1, an on-orbit TSS during the station-keeping phase is orbiting the Earth, with O_E being the center of the Earth. A taped-shaped tether connects the mother spacecraft M and the satellite S. The mass of the mother spacecraft is much larger than the mass of the satellite, i.e., $m_M >> m_S$. The length, width, and thickness of the tape tether are L, d_w, and d_t, respectively, with $d_w >> d_t$. The mass density of the tape tether is ρ_L. The inclination angle between the equatorial and orbital planes is δ. The in-plane pitch and out-of-plane roll angles of the system are θ and φ, respectively, as shown in Fig. 1(b).

An Earth-centered inertial frame is denoted as O_E–$X_E Y_E Z_E$. The origin O_E is at the center of the Earth; the X_E-axis points in the direction of the ascending node, the Z_E-axis is perpendicular to the orbital plane, and the Y_E-axis completes the right-handed coordinate system. An orbital reference frame is denoted by o–xyz.

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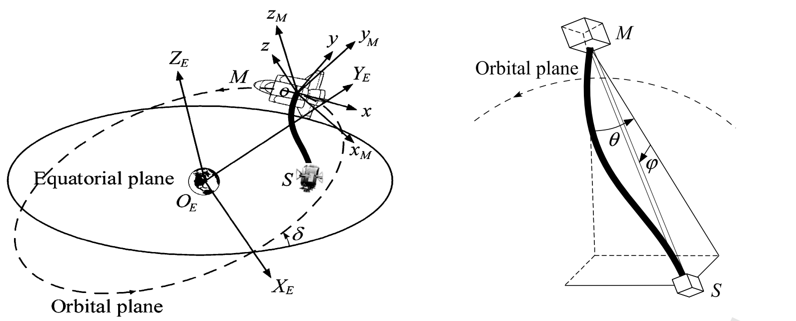
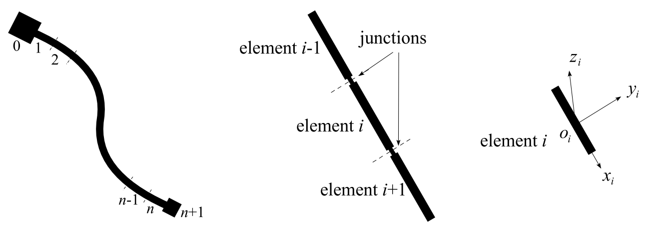


(a) Definitions of the reference frames (b) Definitions of the in-plane and out-of-plane angles

Fig. 1. Description of the two-body TSS.



(a) Discrete flexible tether (b) Rigid element model (c) Body reference frame

Fig. 2. Discretization of the tape-shaped tether.

The origin of this frame is located at the center of the mother spacecraft. The x-axis is in the opposite direction of the motion of the mother spacecraft, the y-axis is along the line connecting O_E to o, and the z-axis completes the right-handed system. In addition, a body reference frame o–$x_M y_M z_M$ is fixed to the mother spacecraft.

The tape tether is divided into n uniform rigid elements marked by $i = 1, 2, \ldots, n$, as shown in Fig. 2. The mother spacecraft M and the satellite S are indicated by 0 and $n+1$, respectively. Similarly, a body reference frame o_i–$x_i y_i z_i$ is fixed to the rigid element i with o_i as the center of mass of the rigid element i. The junctions between the rigid elements are modeled as equivalent linear springs and dampers. It is obvious that such a system of rigid bodies is capable of characterizing the tape tether in dynamics if the number of rigid elements is large enough, and the junctions could be modeled correctly via the equivalent springs and dampers.

According to Newton's second law, the translational motion of the ith rigid element is written as

$$m_i \ddot{\boldsymbol{r}}_{ci} = \boldsymbol{G}_i^E + \boldsymbol{P}_i + \boldsymbol{R}_i, \tag{1}$$

where the dot denotes the derivative with respect to time t. $m_i = \rho_L L/n$ represents the mass of rigid element i, and $\boldsymbol{r}_{ci}$ represents the position vector of the center of mass of the rigid element i in O_E–$X_E Y_E Z_E$. The gravity model in O_E–$X_E Y_E Z_E$ is [19]

$$\boldsymbol{G}_i^E = -\frac{\mu_E}{r_{ci}^2} \times \begin{bmatrix} \{m_i + \frac{3}{2r_{ci}^2}[(3J_{x_i x_i} + J_{y_i y_i} + J_{z_i z_i} - 5Q - 10\tilde{Q}) \\ \quad + \frac{2}{\gamma_{x_i}}(\gamma_{y_i} J_{x_i y_i} + \gamma_{z_i} J_{x_i z_i})]\}\gamma_{x_i}\boldsymbol{i}_i \\ \{m_i + \frac{3}{2r_{ci}^2}[(3J_{y_i y_i} + J_{z_i z_i} + J_{x_i x_i} - 5Q - 10\tilde{Q}) \\ \quad + \frac{2}{\gamma_{y_i}}(\gamma_{z_i} J_{y_i z_i} + \gamma_{x_i} J_{y_i x_i})]\}\gamma_{y_i}\boldsymbol{j}_i \\ \{m_i + \frac{3}{2r_{ci}^2}[(3J_{z_i z_i} + J_{x_i x_i} + J_{y_i y_i} - 5Q - 10\tilde{Q}) \\ \quad + \frac{2}{\gamma_{z_i}}(\gamma_{x_i} J_{z_i x_i} + \gamma_{y_i} J_{z_i y_i})]\}\gamma_{z_i}\boldsymbol{k}_i \end{bmatrix}, \tag{2}$$

where $\mu_E = 3.9885 \times 10^{14}$ m^3/s^2, $Q = \gamma_{x_i}^2 J_{x_i x_i} + \gamma_{y_i}^2 J_{y_i y_i} + \gamma_{z_i}^2 J_{z_i z_i}$, and $\tilde{Q} = \gamma_{x_i}\gamma_{y_i} J_{x_i y_i} + \gamma_{x_i}\gamma_{z_i} J_{x_i z_i} + \gamma_{y_i}\gamma_{z_i} J_{y_i z_i}$, where γ_{x_i}, γ_{y_i}, and γ_{z_i} represent the direction cosine of $\boldsymbol{r}_{ci}$ in o_i–$x_i y_i z_i$, and $J_{x_i x_i}$, $J_{y_i y_i}$, $J_{z_i z_i}$ and $J_{x_i y_i}$, $J_{x_i z_i}$, $J_{y_i z_i}$ are the inertial moments and the products of inertia, respectively. $\boldsymbol{i}_i$, $\boldsymbol{j}_i$ and $\boldsymbol{k}_i$ are the unit vectors of the coordinate axes x_i, y_i and z_i, respectively. $\boldsymbol{P}_i$ is the resultant tension force on the rigid element i exerted by the two junctions, and $\boldsymbol{R}_i$ is the resultant applied force. Note that the inertia matrix of the rigid element i in the fixed body frame o_i–$x_i y_i z_i$ is given by

$$J_i = \begin{bmatrix} J_{x_i x_i} & J_{x_i y_i} & J_{x_i z_i} \\ J_{y_i x_i} & J_{y_i y_i} & J_{y_i z_i} \\ J_{z_i x_i} & J_{z_i y_i} & J_{z_i z_i} \end{bmatrix}. \tag{3}$$

Assume that a uniform atmospheric drag force acts on the rigid element i, i.e.,

$$\boldsymbol{R}_i^d = -\frac{1}{2}\rho_i C_{Di} A_i \boldsymbol{v}_{ri} |\boldsymbol{v}_{ri}|, \tag{4}$$

where ρ_i is the atmospheric density near rigid element i, C_{Di} and A_i are the drag coefficient and the frontal area for the rigid element i, respectively, and $\boldsymbol{v}_{ri}$ is the relative velocity of the rigid element i with respect to the atmosphere. Note that the frontal area of a tape-shaped tether is much larger than that of a string tether.

According to the theory of angular momentum, the attitude equation of motion of rigid element i is

$$\boldsymbol{J}_i \cdot \dot{\boldsymbol{\omega}}_i + \boldsymbol{\omega}_i \times (\boldsymbol{J}_i \cdot \boldsymbol{\omega}_i) = \boldsymbol{M}_i^G + \boldsymbol{M}_i^{P_i} + \boldsymbol{M}_i^b + \boldsymbol{M}_i^t + \boldsymbol{M}_i^R, \tag{5}$$

where $\boldsymbol{J}_i = \boldsymbol{e}_i^{\mathrm{T}} J_i \boldsymbol{e}_i$ represents the inertia tensor of the rigid element i, $\boldsymbol{e}_i$ is a basis vector of the body frame o_i–$x_i y_i z_i$, $\boldsymbol{\omega}_i$ is the angular velocity vector of rigid element i, and the principal gravity moment is

$$\boldsymbol{M}_i^G = \frac{3\mu_E}{r_{ci}^3}\begin{bmatrix} (J_{z_i z_i} - J_{y_i y_i})\gamma_{y_i}\gamma_{z_i} + (J_{x_i z_i}\gamma_{y_i} - J_{x_i y_i}\gamma_{z_i})\gamma_{x_i} \\ \quad + J_{y_i z_i}(\gamma_{y_i}^2 - \gamma_{z_i}^2)\boldsymbol{i}_i \\ (J_{x_i x_i} - J_{z_i z_i})\gamma_{z_i}\gamma_{x_i} + (J_{x_i y_i}\gamma_{z_i} - J_{y_i z_i}\gamma_{x_i})\gamma_{y_i} \\ \quad + J_{x_i z_i}(\gamma_{z_i}^2 - \gamma_{x_i}^2)\boldsymbol{j}_i \\ (J_{y_i y_i} - J_{x_i x_i})\gamma_{x_i}\gamma_{y_i} + (J_{y_i z_i}\gamma_{x_i} - J_{x_i z_i}\gamma_{y_i})\gamma_{z_i} \\ \quad + J_{x_i y_i}(\gamma_{x_i}^2 - \gamma_{y_i}^2)\boldsymbol{k}_i \end{bmatrix}. \tag{6}$$

Moreover, $\boldsymbol{M}_i^{P_i}$ denotes the moment of force $\boldsymbol{P}_i$ about the center of mass of rigid element i, $\boldsymbol{M}_i^b$ and $\boldsymbol{M}_i^t$ are the bending moment and the torque arising from junctions, respectively, and $\boldsymbol{M}_i^R$ the resultant external moment acting on the center of mass o_i of rigid element i.

In the discretized multi-body system, Equations (1) and (5) determine the dynamics of the tape-shape tethered TSS.