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Analytical deployment control law for a flexible tethered satellite system

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ABSTRACT

The deployment process of a tethered satellite system in a space environment is by nature unstable due to the negative-damping effect in the system. Hence, this paper addresses the deployment stability in controlling a space flexible tethered satellite in which the perturbations from a space environment, such as the J_2 perturbation, air drag force, and solar pressure, are considered. An analytical tether length rate control law for the deployment is presented by using a simplified elastic rod model of the flexible tethered satellite. Then, the stability of the controlled time-varying system during deployment is analyzed via the Floquet theory. The parameter regions for stable deployment are obtained to maintain a tensile state of the tether during the deployment phase. The numerical simulations show that the proposed analytical control law is capable of suppressing the in-plane oscillation of the flexible tethered satellite during deployment while maintaining deployment stability.

1. Introduction

In recent years, space tethers have attracted much attention in many applications such as electrodynamic tether applications, active debris removal, tether assisted observation, and debris capture [1–4]. Space missions on tethered satellite systems operate only when the tether is deployed successfully [5–10]. The flexible tethered satellite would exhibit an unstable motion during deployment in the absence of control.

Many researchers have paid attention to deployment control of tethered satellite systems. For example, on account of the weak formulation of equations of the tethered satellite system, the dynamic deployment process subject to the braked, Kissel's, or optimal controls is investigated by Barkow et al. [11]. Based on the small expendable deployer system (SEDS) mission, configuration changes of a flexible tether during controlled deployment on a circular orbit are simulated by Krupa et al. [12]. A methodology for deployment/retrieval optimization of the tethered satellite system is presented by Williams [13], in which the tether is treated as an inelastic straight rod. Taking the J_2 perturbation and the heating impact into account, Yu et al. [14] studied the dynamics of a flexible tethered satellite deployed at a single speed and found that Kissel's control law has a strong impact on the attitude of the spacecraft during deployment [15]. With the assumption of positive tension of the inextensible and massless tethers, the stability of a rotating triangular tethered satellite formation near the L_2 libration point during the deployment/retrieval phase is numerically analyzed by Cai et al. [16]. A fractional-order tension control law for the deployment control of a tethered satellite system is proposed by Sun et al. [17], which shows that the stable region of the classic integer-order tension control is included in that of the fractional-order tension control. For a thin, rigid rod model of the tether, the thrust-aided deployment dynamics and its stability of a long tape-shaped tether deployed from an orbiting spacecraft are addressed by Mantellato et al. [18]. Using tether nets to accomplish active debris removal is discussed by Benvenuto et al. [19]. It is shown that a tethered-net system is useful for capture and removal of space debris. On account of the lumped-parameter model, the overall geometrical and dynamical properties of tether nets in the deployment and capture phases are revealed by Botta et al. [20], and the effect of the bending stiffness modeling is assessed. Based on a rigid rod model, a nonlinear tension control law for space tether deployment is designed by Wen et al. [21], in which the positive tension constraint is explicitly accommodated in a special form of the saturation function. Meanwhile, a nonlinear model predictive control for stabilizing the deployment/retrieval process of a space tether system is also presented by Wen et al. [22].

Previous work has shown that it is difficult to find analytical solutions of the complicated nonlinear model of the tethered satellites, while the simplified linearized model results in large errors.

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Nomenclature

a_m	semi-major axis of the orbit
$\boldsymbol{B}$	monodromy matrix
C	quadratic polynomial
C_{Di}	drag coefficient of node i
c_0, c_1, c_2	coefficients of a quadratic polynomial
EA	stiffness of the tether
e	eccentricity of the orbit
$\boldsymbol{e}_{S_i}$	unit vector of S_i
$\boldsymbol{f}$	vector field of the state equations of the system
f_i	components of vector field
$\boldsymbol{g}_i$	gravitational acceleration of the node i
$\boldsymbol{g}_{M(S)}$	gravitational acceleration of the mother satellite or sub-satellite
J_2	harmonic coefficient
L	total length of the tether
L_e	unstrained length of the tether element
l	length of tether outside the satellites
l_r	reference tether length
l_0	original length of tether outside the satellites
m_i	mass of node i
$m^0_{M(S)}$	mass of the mother satellite or sub-satellite
$\tilde{m}$	non-dimensional mass
n	number of the tether elements
$n_{M(S)}$	number of nodes of tether contained in the mother satellite or sub-satellite
$\boldsymbol{P}_{i,j}$	pulling force applied by node i to node j
$\boldsymbol{P}_{M(S)}$	tether pulling force acting on the mother satellite or sub-satellite
$\boldsymbol{P}_{0(n+1)}$	tether pulling force acting on the mother satellite or sub-satellite
P_2	Legendre polynomials of degree 2
Q_θ	generalized force corresponding to θ
Q_ϕ	generalized force corresponding to ϕ
q	solar pressure constant
R_E	Earth's mean radius
$\boldsymbol{R}_i$	resultant external forces acting on the node i
$\boldsymbol{R}_i^d$	air drag force acting on the node i
$\boldsymbol{R}_i^s$	solar pressure acting on the node i
$\boldsymbol{R}_{M(S)}$	resultant external forces acting on the mother satellite or sub-satellite
$r(\nu)$	distance between the center of the mass of the system and the center of the Earth
$\boldsymbol{r}_i$	position vector of the node i
$\boldsymbol{r}_{M(S)}$	position vector of the mother satellite or sub-satellite
S_i	frontal area of the ith tether element or the satellites
$s_{M(S)}$	length of tether in the mother satellite or sub-satellite
T	tensional force along the tether
t	time
u	non-dimensional tensional force
$\boldsymbol{v}_{ri}$	relative velocity of node i to atmosphere
(X, Y, Z)	position in the inertial coordinate frame
(x, y, z)	position in the orbital coordinate frame
α	dissipation constant of the tether
β_i	reflectivity of the ith tether element or the satellites' surface
γ_i	angle between the normal directions of the effective area and the Sun's rays for the ith tether element or the satellites
ε	strain of the tether based on elastic rod model
$\varepsilon_{\mathrm{ave}}$	mean strain of the tether
$\varepsilon_{i,j}$	strain of the tether segment between node i and node j
$\varepsilon_{\max}$	maximum strain
$\varepsilon_{\min}$	minimum strain
ε_0	initial strain
$\eta_{i,j}$	elongation of the tether segment between node i and node j
θ	in-plane pitch angle
θ_e	expected in-plane pitch angle
θ_e^{inf}	infimum of expected in-plane pitch angle
θ_e^{upp}	supremum of expected in-plane pitch angle
ϑ_i	geocentric latitude of node i
κ	parameter equaled to $1 + e\cos\nu$
λ_i	Floquet multipliers
μ_E	Earth's gravitational constant
ν	true anomaly
ν_0	initial true anomaly
ξ	non-dimensional deployed tether length
ξ_0	initial non-dimensional tether length
ρ_i	atmospheric mass density of the space where the node i is located
ρ_L	linear density of the flexible tether
$\varPhi$	integral variable matrix
φ_i	state variables of the system
φ_{ie}	expected state variables
ϕ	out-of-plane roll angle
ϕ_e	expected out-of-plane roll angle
(χ, η, ζ)	position in the non-dimensional coordinate frame
$(\,)'$	differential operation with respect to time
$\dot{(\,)}$	differential operation with respect to true anomaly

In general, the deployment control strategies of tensional force and tether length often perform well in a circular or nearly circular orbit around the Earth. The eccentricity of the orbit is usually restricted to a small range. However, once the calculated tether tensional force is less than zero in the process of deployment, the control force is sometimes forced to zero. These strategies may not be very reasonable. To the author's knowledge, a parameter domain that guarantees that the tether remains in a tensile state has not been presented. In addition, not all deployment control laws derived from the simplified model apply to the complicated flexible tether model closed to the original system. Moreover, the stability of the control laws is also subject to environmental perturbations.

In this paper, an analytical control law for flexible tethered satellite systems in three-dimensional space is proposed. This study begins with the flexible tether and elastic rod based modeling of a tethered satellite in Sec. 2. An analytical control law on tether length rate is given in Sec. 3. The parameter regions for the tensile state of the tether are given in Sec. 4, and finally, numerical simulations are given in Sec. 5.

2. Formulations of tether model

2.1. Flexible tether model

As shown in Fig. 1, the flexible tethered satellite system consists of a mother satellite M and a sub-satellite S with mass m_M^0 and m_S^0, respectively. The two satellites are connected by a flexible viscoelastic tether of unstrained length L wound on a spool of a deployment device in the satellites. To reveal the dynamic behaviors of the tethered satellite system, an inertial geocentric frame *O-XYZ* is established in Fig. 1 such that the X-axis is in the di-