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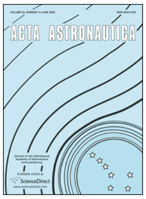

Modeling of tape tether vibration and vibration sensing using smart film sensors

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ABSTRACT

Tape-tethered satellite systems use long and flexible tape tethers, the bending and torsional vibrations of which affect the positions and attitude of attached satellites and climbers. Owing to the distribution characteristics of a tape tether, ordinary point sensors and actuators cannot be used easily to control the vibrations. Other types of sensors and actuators are required for this purpose. The flexibility and deformability of smart materials make them particularly suitable for integration into a tape-tethered system. Thus, in this paper, we propose a method for modeling the bending and torsional vibrations of a tape tether, and report our investigation into the feasibility of using smart film sensors to distinguish between the two vibration types. We formulate equations of motion for the tape tether using multibody dynamics techniques, and perform numerical simulations to study the behavior of the bending and torsional vibrations. The results of our experiments show that the bending and torsional vibrations of a tape tether can be measured using smart film sensors attached to the tether.

1. Introduction

Tethered satellite systems (TSS) are emerging space technologies. A TSS generally comprises a mother satellite, one or more subsatellites, and a very long tether that connects all the satellites. TSSs facilitate satellite orbit transfer, formation systems, transportation, subsatellite attitude control, and other tasks [1]. The space elevator (SE) is the ultimate configuration of a TSS and includes a subsystem for transportation from the ground into space. Electrodynamic tether (EDT) systems, which use the Lorentz force derived from the interaction between the electric current on the tether and Earth's magnetic field, have the potential to function as space debris removal systems. However, the practical application of the TSSs remains difficult, especially because of the highly complex nonlinear dynamics of the tether. In space, tethers are expected to be deployed over 1 km with the tension in them to vary along their length. Thus, the vibration of the tether cannot be treated as a string vibration. The tether motion is affected by not only external forces such as gravity but also the Coriolis force because the tether of tethered satellite systems moves in the orbital frame that orbits around the Earth with an orbital angular velocity. If the tether is subject to vibrational excitation in space, the damping would be minimal owing to the almost negligible drag force. There is also a possibility of the tether becoming slack, and in such case, it could not be used to control the satellites at its ends. In addition, the vibration of the tether may disturb the attitude of the mother satellite, the subsatellites, and a climber [2–4] traveling along the tether. Thus, the dynamics of a TSS is highly complex and very difficult to model. In particular, flexibility and three-dimensional motion must be considered in modeling of the tether. Extensive studies have been conducted on modeling of flexible beams [5–7], cables [6,8,9], plates and membranes [10], using

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Nomenclature

$\boldsymbol{A}_i$	skew matrix including $\omega_{i,x}$, $\omega_{i,y}$ and $\omega_{i,z}$
A	section area of the tape tether
$\boldsymbol{b}_i$	bi-normal unit vector of the tape tether
$\boldsymbol{D}_i$	direct cosine matrix from $(i-1)$th director to ith director
d	distance from the tether end to the mass center of the end body
E	Young's modulus of tape tether
$\boldsymbol{F}_{\text{ex}}$	external force and internal (structural) damping force affecting the ith segment
$\boldsymbol{F}_i$	total force affecting the ith segment
G	shear modulus
$\boldsymbol{g}$	gravity acceleration vector, $\boldsymbol{g} = (0.0, 0.0, 9.8)^T$ (m/s^2)
h	torsional rigidity $= GJ$
I_y, I_z	moments of inertia of a section area about the y- and z-axes
J	polar moment of inertia of a section area
J_x, J_y, J_z	moments of inertia of the end body
K	bending stiffness $= EI$
k	spring constant $= EA$
l_i	length of spring between ith and $(i+1)$th mass
l	assumed natural length of a spring between discrete tether segments
M_i^l	bending moment of left side of ith mass
M_i^r	bending moment of right side of ith mass
m	mass of one tether segment
m_{end}	mass of the end body $(= m_{n+1})$
$\boldsymbol{N}_i$	axial force
n	number of masses representing tether
$\boldsymbol{n}_i$	normal unit vector of tether plane
$P_{i,j}$	components of $\boldsymbol{D}_i$
Q_i	shear force
$\boldsymbol{R}_i$	moment torque perpendicular to axial unit vector
$\boldsymbol{r}_i$	position vector of ith mass
$\boldsymbol{T}_i$	matrix including $\boldsymbol{t}_i$, $\boldsymbol{b}_i$, and $\boldsymbol{n}_i$
$\boldsymbol{t}_i$	axial unit vector of ith segment
$\boldsymbol{U}_i$	matrix including U_i, V_i, and W_i
U_i, V_i, W_i	velocity components, resolved along directions $\boldsymbol{t}_i$, $\boldsymbol{b}_i$, $\boldsymbol{n}_i$
α_i	angle between vectors $\boldsymbol{t}_i$ and $\boldsymbol{t}_{i-1}, \alpha_i = \cos^{-1}(\cos\theta_i \cos\phi_i)$
ϕ_i, θ_i, ψ_i	Euler angles around $\boldsymbol{n}_i$, $\boldsymbol{b}_i$, $\boldsymbol{t}_i$
ρ	mass per unit length of the tape tether
$\boldsymbol{\Omega}_i$	general moment of force (torque) due to deformation
$\boldsymbol{\omega}_i$	angular velocity of ith segment $\boldsymbol{\omega}_i = (\omega_{i,x}, \omega_{i,y}, \omega_{i,z})^T$
ζ_x, ζ_y, ζ_z	damping coefficient related to the angular velocity
ζ_t	damping coefficient related to the longitudinal velocity

floating reference frame, Frenet frame, or absolute nodal coordinate frame, many previous studies on space tethers did not utilize such useful models or techniques, but assumed string tethers and focused only on the transverse and pendulum oscillations [4,11–13].

However, tape tethers are more durable than string tethers when exposed to space debris, and effective EDT systems require a large area for the collection of electrons on the tether surface from the plasma in space. In addition, torsional vibration cannot be ignored in tape tethers considering their width. NASA observed the torsion of a tether during a mission of the Gemini 11 Agena Target Vehicle in 1966, and video recordings made by the organizers of the Japan Space Elevator Technical and Engineering Competition (JSETEC) showed a belt tether exhibiting torsional vibration, which was affected by the wind and a climber [14]. Furthermore, during the T-Rex mission [15], a tape tether twisted after it was deployed from a slowly rotating rocket [16]. In general, point-type sensors and actuators are used to control the vibration of beams, plates, and strings. However, it is difficult to apply such sensors to tape tethers because of their length, climber movement, and use of a deployment mechanism such as a reel. To overcome these difficulties, we propose the use of smart film sensors for sensing the vibration of a tape tether. Although several studies have been conducted on the deployment of tape tethers [17,18], to the best of our knowledge, none have used smart film sensors to measure the vibration of the tether. In this paper, we describe such smart films, propose a method for modeling a tape tether using discrete segments, and present the results of numerical simulations performed using the proposed model. The experimental results confirm that the bending and torsional vibrations of a tape tether can be separately measured by smart film sensors pasted at appropriate locations on the surfaces of the tether.

2. Smart film sensors and actuators

Methods for controlling the vibration of flexible beams and planar structures using smart film sensors and actuators have recently been investigated [19–21]. Smart films such as piezoelectric materials have sensing and actuation capabilities [22] and are characterized by flexibility, lightness, thickness, and ease of processing, which facilitate their integration into structures and controllers.

Previous studies have demonstrated that smart films can be used to determine the vibration mode of a structure without detrimental effects to the structure's properties. Fig. 1 shows an example of the detection of a vibration wave using smart film sensors [23]. In this case, the sensors are used to determine the (1, 3) or (2, 3) vibration mode of the plate. Fig. 1(a) shows the (3, 3) mode wave, where the dotted lines are the nodal lines of the mode of the plate. Fig. 1(b) shows the shape of the film sensors and their location on the plate. The (1, 3) mode wave can be obtained by combining the signals from sensors 1 and 2. In addition, information about the (2, 3) mode wave can be