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Cluster filtering/control of bending/torsional vibrations of a tape tether using smart-film sensors/actuators

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ABSTRACT

Tape tethers show great promise for application in space debris removal because they possess a large collecting area, which is crucial for the collection of electrons from a plasma environment in space. Tape tethers are therefore preferred over string tethers in electrodynamic tethered systems (EDTS), which operate based on the Lorentz force derived from the interaction between the electric current on the tether and the Earth's magnetic field. Vibrations of the tether may disturb the attitude of the mother satellite and the subsatellite, and are difficult to damp in space because the damping would be minimal owing to the almost zero drag force in space. Due to their relatively large width, tape tethers experience torsional deformation and therefore cannot be treated as a string tether. If torsional deformation of tape tethers is not avoided, the advantage of tape tethers as the materials for EDT systems will be deteriorated. Point-type sensors and actuators are usually used to sense and control vibrations. However, it is difficult to apply such sensors and actuators to tape tethers because of the substantial length of the tether as well as the need for a deployment mechanism, such as a reel. In order to overcome the difficulties related to vibrations, the use of smart-film sensors and actuators for sensing and controlling vibrations of tape tethers is considered in this study. In a previous study, we presented an application of smart film for sensing vibrations of tape tethers, but the actuation of tape tethers using smart-film actuators has not yet been reported. In the present paper, we mathematically derive suitable configurations of smart-film attachment to a tape tether for cluster filtering and actuation of bending and torsional vibrations of the tape tether, and carried out cluster actuation experiments. The experimental results reveal that the bending and torsional vibrations of a tape tether can be reduced by cluster actuation control based on direct velocity feedback control (DVFC) using smart-film sensors/actuators attached to the surface of the tape tether with the derived configurations.

1. Introduction

Many future space missions will use tethered satellite systems (TSS) for satellite orbit transfer, satellite formation systems, transportation of materials and personnel, and subsatellite attitude control [1]. Although several experimental missions have been carried out in space, it is still difficult to realize practical applications of TSSs in space, because tether tension varies with the length of the tether, which is expected to exceed one kilometer to be effective as a long connector.

Electrodynamic tethered (EDT) systems, which are one of the TSS configurations, make use of the Lorentz force generated from the interaction between an electric current on the tether and the Earth's magnetic field, and are expected to be used in space debris removal systems. A large surface area is required for EDT systems to effectively collect electrons on the tether surface from the plasma environment in space. Tape tethers are more desirable than string tethers for EDT systems because they can more efficiently collect electrons.

The deployment and retrieval of a tethered subsatellite induces a Coriolis effect on the tethered subsatellite, which leads to pendulum oscillation of the tether [2–4]. Moreover, tethers experience vibrations due to the motion of a climber traveling along them [5–15], and these vibrations may disturb the attitude of the mother satellite, the subsatellite, and the climber. A number of previous studies on tethers assumed string tethers, and focused solely on string and pendulum vibrations [2–15]. Once a tether begins to vibrate in space, the vibrations cannot be easily damped, because the damping effect would be minimal due to the almost zero drag force in space. In addition, due to the relatively large width of tape tethers, torsional vibrations cannot be ignored [16]. In other words, the string model is inadequate for the description of tape

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Nomenclature

$\mathbf{b}$	unit vector along the short side of the tape tether
D	distance from the tether end to the center of mass of the end-body
e_{31}, e_{32}	directional piezo-electric field intensity coefficients
g	acceleration of gravity, $g=9.8$ m/s^2
J_x, J_y, J_z	moments of inertia of the end-body
L	tether length
m	mass of the end-body
$\mathbf{t}$	unit vector along the long side of the tape tether
V_s	output voltage signals of the film sensor
$w(x, y)$	deflection of the film in the z direction at (x, y)
x_1, x_2	boundaries of the film in the x direction
$y_i(x), y_{ij}(x)$	boundary functions of the film in the y direction $(i = 1, 2, j = 1, 2)$
$\alpha, \alpha_1, \alpha_2$	inclined angle of film fiber with respect to the long side of the tape tether
Γ	amplifier coefficient

tethers. In fact, the torsion of a tether was observed during a mission of the Gemini 11 Agena Target Vehicle in 1966, and a tape tether used for the T-Rex mission [16] twisted after it was deployed from a slowly rotating rocket [17]. Point-type sensors and actuators are usually used for sensing and suppressing structural vibrations, but are not suitable for sensing and controlling vibrations of distributed system such as beams and plates, because distributed systems have an infinite number of structural vibrational modes. Similarly, it is impractical to apply point-type sensors and actuators to tape tethers in order to suppress tether vibrations because the tethers are distributed systems and are expected to be deployed over one kilometer. Furthermore, a deployment mechanism must be included in the system. For the above reasons, applications of smart-film sensors and actuators have recently been widely studied for sensing and controlling vibrations of beams and plates [18–20]. However, the application of smart films to tape tethers has not yet been widely investigated. As the first attempt of the application of smart films to tape tethers, the use of smart-film sensors was experimentally investigated in [21]. In that study, a parallel configuration of smart films, whereby two smart films were attached to both sides of the free end of the tape tether in order to sense the bending and torsional vibrations, was considered. However, the mathematical validity of the parallel configuration of the smart-film sensors was not reported in [21], and the use of smart actuators to control vibrations of tape tethers has not yet been reported in the literature.

In the present paper, proper configurations of smart-film attachment to tape tethers are mathematically derived for cluster filtering and actuation of bending and torsional vibrations, and experimental results for cluster actuation are presented. The experimental results reveal that the bending and torsional vibrations of tape tethers can be reduced by cluster actuation control based on DVFC [22] using smart-film sensors/actuators attached to the surface of the tape tether with the derived configurations.

The remainder of the present paper is organized as follows. In Section 2, configurations of smart films for cluster filtering and actuation are mathematically derived. In Section 3, experimental results are presented in order to validate the derived configurations for sensing and controlling the vibrations of the tape tether. Finally, conclusions are presented in Section 4.

2. Configuration of smart films for cluster filtering and actuation

Recently, several methods of vibration control for flexible beams and planar structures using smart-film sensors and actuators have been presented [18–20]. The objective of the present study is to separately monitor the bending and torsional vibrations of tape tethers and control these vibrations using smart-film actuators. In the present study, we assume that a small segment of a tape tether can be modeled as a rectangular plate. Under this assumption, by referring to past studies, we derive appropriate attachment configurations of smart-film sensors and actuators to tape tethers for separately sensing and controlling bending and torsional vibrations.

2.1. Schematic representation of cluster filtering by point-type sensors

Before considering the conditions of film sensors for separately sensing bending and torsional vibrations, in the following, point-type sensors are used to explain the concept of cluster filtering. Fig. 1 shows a schematic representation of cluster filtering. We assume that two point-type sensors, denoted “a” and “b”, are attached to each side of the plate, and both point-type sensors detect the acceleration of the corresponding side. Let us suppose that both bending and torsional vibrations exist in the plate and that any vibration can be represented as combination of these two types of vibrations. Point-type sensors “a” and “b” output in-phase signals for the case of bending vibrations, whereas these sensors output anti-phase signals for the case of torsional vibrations. From this point of view, bending vibrations can be detected by adding the signals from both sensors “a” and “b”, whereas torsional vibrations can be detected by subtracting the signals of one sensor from those of the other sensor. Similarly, bending vibrations can be controlled by two in-phase point-type actuators attached to each side of the plate, whereas torsional vibrations can be controlled by two anti-phase point-type actuators attached to each side of the plate. This is the basic mechanism of the cluster filtering and actuating method.

2.2. Output signal from one film sensor

With regard to the cluster filtering method explained above, we consider configurations required for the film sensors to distinguish bending and torsional vibrations from each other. In the present study, two configurations of the film sensors, namely parallel and inclined configurations, as shown in Figs. 2 and 3, are considered.

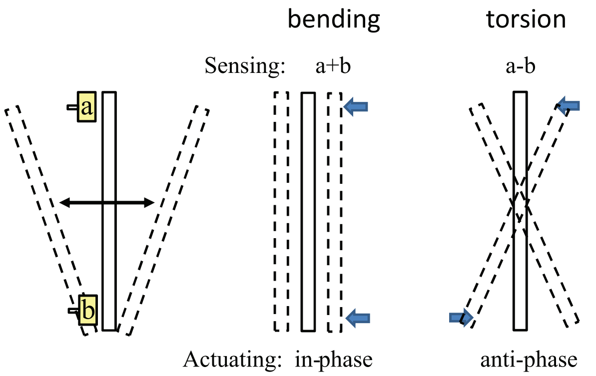

Fig. 1. Cluster filtering and control for bending and torsion using point sensors.