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Review of Dynamics and Control of Nonelectrodynamic Tethered Satellite Systems

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Nomenclature

a	=	semimajor axis of the system center of mass, m
e	=	orbital eccentricity
I_k	=	satellite principal centroidal moment of inertia about k axis, $k = x, y, z$, $\text{kg} \cdot \text{m}^2$
K_1, K_2	=	satellite mass distribution parameter, $(I_x - I_y)/I_z$, $(I_x - I_z)/I_y$
L	=	distance between mass centers of satellites m_1 and m_2, tether length if $m_1 \gg m_2$, m
L_0	=	initial tether length, m
M	=	total system mass, kg
m_i	=	mass of satellite i, kg
m_t	=	tether mass, kg
$\boldsymbol{r}_i$	=	position vector of mass m_i from the system center of mass, m
$\hat{\boldsymbol{r}}_1$	=	r_1/a
β, η	=	relative in-plane and out-of-plane swing angles between m_1 and m_2, respectively, deg
$\beta_{\max}, \eta_{\max}$	=	maximum values of β and η, respectively, deg
$\dot{\beta}_0$	=	$\dot{\beta}$ at $\theta = 0$
ΔH_{a1}	=	maximum altitude decrease of m_1 at apogee, m
ΔH_i	=	altitude gain of satellite mass m_i, m
ΔH_{p2}	=	maximum altitude gain of m_2 at perigee, m
ΔL	=	decrease in the initial tether length L_0 during tether retrieval, m
δ	=	ratio of in-plane swing rate $\dot{\beta}$ to the orbital rate Ω
μ	=	gravitational constant, m^3s^{-2}
Ω	=	orbital rate, $(\mu/a^3)^{1/2}$, rad/s

I. Introduction

THE concept of a space tether, an "Orbital Tower," was first conceived by Tsiolkovsky[1] in 1895. In 1974, Colombo et al.[2] put forward the proposal of a "Shuttle-borne Skyhook" for low-orbital-altitude research, thus marking the advent of tethered satellite systems (TSS). Since then, several interesting space applications of tethers[3] have been proposed and analyzed. Several missions have already been flown to verify the TSS concept.[3] These include NASA's Gemini 11 and 12 in 1967 (Ref. 4); a joint U.S.–Japanese space project called the Tethered Payload Experiment, Charge-1 in 1983 and Charge-2 in 1984 (Ref. 5); the Canadian Space Agency's Observation of Electric-Field Distributions on the Ionospheric Plasma—a Unique Strategy (OEDIPUS) Missions, OEDIPUS-A in 1989 and OEDIPUS-C in 1995 (Refs. 6 and 7); NASA and Italian Space Agency's (ASI) TSS-1 in 1992 and TSS-1R in 1996 (Ref. 8); NASA's Small Expendable Deployer System (SEDS) missions, SEDS-1 in 1993 and SEDS-2 in 1994 (Ref. 9); NASA's Plasma Motor Generator (PMG) Experiment in 1993 (Ref. 10); the U.S. Naval Research Laboratory's tether physics and survivability (TiPS) in 1996 (Ref. 11); and the advanced tether experiment (ATEx) in 1998 (Ref. 12). Descriptions of these missions, as well as future tether missions, have been presented by Cosmo and Lorenzini.[3] The results of successful tether missions[3] clearly establish that the basic tenets of the TSS concept are sound and that the TSS can be deployed to long distances.

The dynamics and control aspects of the TSS have received considerable attention by several researchers in the last two decades. An excellent review of earlier studies was presented by Misra and Modi[13] in 1986. In the 1990s, tether-related activities were actively pursued, and a large number of papers were added to the literature. It seems, therefore, pertinent to review the papers that have appeared after 1986. However, it is necessary to be selective because the number of papers is quite large, and, therefore, a review on electrodynamic tethers has been omitted, and some of the existing references have been included. The main objective of this paper is to summarize the significant progress that has been made in understanding the intricacies of the dynamics and control aspects of the TSS and to educate beginners and nonspecialists on the exciting problems and challenges involved.

A typical TSS mission involves deployment, station-keeping, and retrieval phases. In its general form, TSS dynamics are quite complex because they are governed by a set of ordinary and partial nonlinear, nonautonomous, and coupled differential equations that may account for the following: three-dimensional rigid dynamics (attitude motion) and flexible motion of the tether connecting bodies, swinging in-plane and out-of-plane librational motion of the tether, longitudinal and transverse vibrations of the tether, and the effect of external forces, for example, gravitational forces, aerodynamic drag, solar radiation pressure, etc. With the aim of obtaining insight into the complex dynamics of the TSS, various simplifications have

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been carried out depending on the dynamic aspects under consideration. These aspects are classified in groups for the review of the pertinent literature.

II. Dynamics and Control of Two Point Masses Connected by Single Tether

Initial investigations considered a system comprising a massive body called the main satellite and an auxiliary mass termed the subsatellite, which is connected by a tether. The tether undergoes in-plane and out-of-plane rigid-body librations that have frequencies of $\sqrt{3}$ and 2 times the orbital frequency, respectively.[13] In the deployment or retrieval phase, the motion of the subsatellite is affected by the Coriolis force and orbital motion. The station-keeping is only marginally stable, whereas the deployment can become unstable if a critical speed is exceeded, and the retrieval is always unstable.[13] The retrieval affects the in-plane libration more strongly than the out-of-plane libration.[13] Whereas the deployment can be controlled with relative ease, the retrieval is more difficult to control because large-amplitude in-plane, as well as out-of-plane, tether librations are excited, and sufficient tension cannot be maintained during the terminal retrieval phase.[13] The problem becomes more complicated when orbital eccentricity and/or aerodynamic forces are significant.[14] To control the TSS during these maneuvers, an open-loop control and its augmentation with a feedback control based on tether tension, tether length rate or range rate, thruster-augmented torque, and combinations of these have been proposed. All of these aspects are reviewed starting with the open-loop control procedure.

A. Open-Loop Control

The deployment can be accomplished using an open-loop approach, that is, without the need for librational feedback control, by uniformly or exponentially changing the tether length in a single stage,[13,15,16] or through a combination of these, that is, uniform–exponential, exponential–uniform, exponential–uniform–exponential, and exponential–exponential, in multiple stages.[13,15] A single-stage sinusoidal law with zero final velocity[15,17] and a two-stage hyperbolic deployment with zero initial velocity and sinusoidal deployment with zero final velocity[15] can also be applied. A passive scheme for the deployment during which the subsatellite mass moves freely in space after initial ejection until the tether becomes taut was proposed by Kane and Levinson[18] for a space station-/shuttle-based tethered system (STSS), wherein the space station/shuttle is a main satellite. However, some damping mechanism may be required at the final stages of the deployment to keep the main satellite and the subsatellite in an Earth-pointing orientation. From analytical solutions of the STSS equations of motion considering some simplifications,[13] it is concluded that, by the use of an exponential law, the tether in-plane angle attains a steady state value of $(\frac{2}{3})c$, where cL is the rate of deployment. With a uniform scheme, however, the system exhibits an in-plane librational motion around a gradually reducing equilibrium angle, and the uniform scheme is thereby very effective for the tether deployment and libration control.[19] The amplitude of the out-of-plane librational motion remains bounded and decreases gradually as the deployment proceeds using the exponential/uniform law. Pascal et al.[15] derived analytical solutions for a TSS in elliptic orbits considering sinusoidal/hyperbolic laws. The sinusoidal deployment scheme is found to give the best result.

The tether deployment in two or three stages results in better system performance compared to a single-stage scheme.[13] The three-stage exponential–uniform–exponential law of deployment is recommended for most missions for which the librational motion of the system is required to come to rest at the end of the deployment.[13,20,21] The two-stage uniform–exponential deployment was proposed by Peláez.[21,22] By judicious selection of the initial rate of deployment and an ejection angle with respect to the local vertical, the proposed scheme[21,22] results in the final libration coming to rest and the tether aligning with the local vertical at the end of the deployment, which occurs the first time the tether crosses the local vertical with a zero angular speed. For a tether-assisted reentry vehicle system, a two-stage exponential (accelerate)–exponential (decelerate) deployment scheme was found to be the best scheme,[23] and this scheme drastically reduces the fluctuations of tether tension that result at the end of the deployment using a single-stage exponential law.[23,24]

In the case of tether retrieval, a single-stage sinusoidal law with zero final velocity[15,17] leads to stable retrieval. In the crawler method,[25] a conventionally deployed subsatellite crawls toward the space shuttle along the tether, and, at the conclusion of the retrieval, the still deployed tether can be jettisoned if required. This approach for the planar TSS motion was later extended to include an out-of-plane tether motion.[26] The analytical solutions of the TSS equations of motion using this method were obtained assuming small in-plane and out-of-plane motions for the TSS in circular/elliptic orbits.[15] The deployment can be accomplished using such passive strategies as appropriate circular, elliptic, or hyperbolic orbits that are utilized for both of the end bodies, and the tether is allowed to become slack during the process of deployment until it is pulled taut at the final stage.[27] Similar approaches have been followed for the tether retrieval.[27] A strategy for regulating the variation of the tether length was presented by Chernousko[28] wherein the tether libration angle vanishes at the end of the retrieval.

B. Open-Loop Control Augmented with Brake Force/Damper

With an open-loop deployment, the system remains stable as long as the rate of deployment is below a critical speed of 0.75 ΩL (Ref. 20). However, this procedure may result in large tether librational motions. In addition, when exponential/linear deployment laws are applied, the speed of deployment becomes highest at the end of the deployment process, resulting in a strong impact and, thereby, high axial stresses in the tether.[29] A large tether librational oscillation, that is, $\beta_{\max} < 65$ deg or $\eta_{\max} < 60$ deg, at the end of the deployment[3] is not problematic for a reentry tethered vehicle system such as SEDS[30] because it causes a larger decrease in the altitude of the reentry capsule. However, in electrodynamic tethered systems such as TSS-1, the tether librational motion is required to be very small throughout the deployment process as well as at the end of the deployment. To solve the problem of large librational motions, the application of passive dampers or brake forces[31,32] has been suggested. When a passive skip-rope damper[31,32] is used, the tether passes through an eyelet ring located at a certain distance away from and anchored to the main satellite. The contact of the tether with the ring passively damps its skip-rope or whirling motion. Alternatively, a force braked process controlled passively or actively in conjunction with an open-loop procedure has been successful in controlling the tether librations.[29,30] A dry friction damper along with the brake force was applied in the SEDS-2 mission. When this approach was applied to the propulsive SEDS (ProSEDS) tether mission with a fuzzy-set technique and finite elements,[33] the deployment was found to be insensitive to variations in material properties, but was sensitive to variations in the initial tether ejection momentum and controller parameters. Although with the incorporation of brake force/dampers the tether libration may become small at the end of the deployment, it may not remain close to the local vertical throughout the process. Therefore, it is imperative to choose control laws that utilize as little feedback information as possible to control the TSS to incur fewer gadgets and less complexity, thereby achieving high system reliability.

C. Tether Tension Feedback Control

A tension control law was first proposed by Rupp[34] based on modulating the tether tension as a linear function of the commanded and actual lengths and the rate of change of length. This in-plane study of the TSS was extended to the three-dimensional tether librational motion by Baker et al.[35] and included the tether mass and aerodynamic forces (and heating) on the tether and subsatellite. In this study,[35] the tether tension could not provide control of the out-of-plane swing motion within the linear range during the local vertical station-keeping phase, but such control is possible in a nonlinear system due to higher-order coupling. The tether tension control using Kissel's law (see Ref. 34) leads to a deployment process that remains close to the radial relative equilibrium configuration, but takes a much longer time for the completion of the deployment because the rate of the tether deployment decreases exponentially in the final phase.[29] It is also possible to develop a tension control law based on linearizing the system equations of motion about the equilibrium point.[36] Levin[37] proposed another tension control law that includes an equilibrium tension required for the uniform vertical motion of the subsatellite, the difference of the tether length and the final desired tether length, and the difference of the corresponding length rate and the reference length rate. During the initial transient phase,[37] the reference length rate is varied using a cosine law that is a function of time, and, afterward, the reference length rate is kept constant at a speed below its initial value.

Another possible way to control the librational motion of the TSS is to include nonlinear feedback terms in a tension control law. This modified tension control law proposed by Modi et al.[38] requires information on tether length, length rate, in-plane tether pitch angle and its rate, as well as the nonlinear out-of-plane tether angular rate. For the station-keeping phase, Liaw and Abed[39] developed a linear controller based on the Hopf bifurcation theorem. The quadratic feedback of the tether out-of-plane angle and/or tether out-of-plane angular rate results in a reduction of the tether out-of-plane librational motion.[39] Liu and Bainum[40] added nonlinear tether in-plane and out-of-plane angles and angular rates to the feedback control (see Ref. 38). The stability conditions involving the tether length and its rate gains for the in-plane motion of a TSS with a flexible tether during station-keeping phase were found to be qualitatively similar to those for the TSS with a rigid tether. Musetti et al.[41] presented a procedure for the deployment of the tether wherein a mission profile for the tether length variation is first designed, followed by step by step computation of tether tension based on a mathematical model and the mission profile. Finally, the tether tension control is implemented in accordance with the computed results. A nonlinear tension control law that takes the tether length and its rate as feedback was proposed by Lorenzini et al.[42] for an in-plane motion of the TSS.

D. Tether Length Rate Control

The librational motion of the TSS can be controlled by changing the tether length rate.[13,43] The tension and length rate control are usually implemented at the deployment spool of the tether. A range-rate control algorithm was applied by Yu,[44] that considered the tether mass and TSS stationary configuration, and, thereupon, the stability of such a configuration was investigated and compared with the numerical solution. Davis and Banerjee[45] extended the concept[35] in which the tether out-of-plane librations are damped using a length-rate control after the tether is deployed/retrieved to the desired length. A yo–yo-type motion is applied for the tether out-of-plane libration damping of the TSS, requiring very high deployment/retrieval rates in relation to the frequency of the tether out-of-plane libration.[45] The retrieval using a tension control law requires some braking on approaching its completion, and the final stage of the retrieval and especially docking need a movable boom augmentation or a thruster augmentation.[46] A fuzzy logic based feedback deployment law can be applied for the in-plane tether deployment using simple fuzzy logic rules and minimal measurements.[47]

E. Optimal Control

Some investigations have treated the tether swing control as an optimization problem. Linear optimal control theory based on the application of the linear quadratic regulator (LQR) method was applied by Bainum and Kumar[48] to develop a tether tension control law based on the linear feedback of tether length, length rate, in-plane tether pitch angle and its rate, as well as the commanded length for the deployment, retrieval, and station-keeping of the subsatellite. With this approach,[48] it was found[49] that the effect of a massive and taut tether was to reduce the stability region in the parametric space obtained by the optimal control gains of Ref. 48. The control laws developed using an approximate linearized stability analysis are effective only under certain conditions, and their implementation requires a feedforward length command that must be chosen carefully for the proper operation of the control laws.[49] A Lyapunov approach was used by Fujii and Ishijima[50] for the design of a deployment/retrieval control law that does not require feedforward length commands. Although the controller performs well, terminal oscillations of the tether length and tension are encountered during deployment, and the pitch angle cannot be controlled at the origin during the terminal phase of the retrieval. Using the same Lyapunov approach, Vadali[51] proposed a velocity control law that allows fast retrieval by attempting to maintain a constant tether pitch angle. In an alternate treatment of the problem, it was concluded that, under similar assumptions, a linear feedback of the tether length and its rate is sufficient to guarantee asymptotic stability of a closed-loop system about a desired equilibrium point. A modified Lyapunov control law developed[51] to eliminate terminal oscillations[50] results in a rapid retrieval if a moderate pitch angle excursion of the tether is allowed during an intermediate phase of the retrieval. In all cases considered,[51] the pitch angle can be controlled to the desired equilibrium point.

The Lyapunov approach was also applied to a tracking-type control by Fujii and Anazawa[52] to obtain a state path that optimizes the time integral of the squared tension plus the squared tether in-plane angle as the performance index, subject to inequality constraints on the control tether tension force. To overcome the difficulty of obtaining the optimal path by solving a two-point boundary-value problem, a stabilized continuation method that converts a two-point boundary value problem into an initial value problem was adopted by Ohtsuka and Fujii.[53] Kokubun et al.[54] applied a real-time optimal state feedback to the TSS control problem. The optimal feedback controller input was derived with the receding horizon control method. A three-dimensional treatment of this problem was provided by Fujii et al.[55] and then by Vadali and Kim,[56] who derived two control laws. The first is based on partial decomposition of the equations of motion, and the utilization of a two-dimensional control law developed in Ref. 51. The other uses a Lyapunov function that takes the out-of-plane motion into consideration. The control laws are found to be effective when used in conjunction with the out-of-plane thrusting.[56] An optimal trajectory using the geometric approach was obtained by Fujii and Kojima[57] by connecting the initial position and the final desirable position of the tethered subsatellite by the shortest length and by selecting the performance index as the Riemann metric to measure the length of trajectory of the subsatellite in the orbital plane. An optimal control strategy for the force controlled deployment was proposed by Barkow et al.[29] with an additional property that the final state is again a radial relative equilibrium. The proposed method[29] was found to be the best method for the fast deployment, although the open-loop deployment is obtained as the fastest deployment associated with long-term large-amplitude oscillations. The application of a targeting approach based on the concept of "targeting" used in controlling chaos[58] results in a reduction in the deployment time, along with a requirement of significantly smaller energy input compared to Kissel's strategy (see Ref. 34). Note that the TSS, being a nonlinear and nonautonomous dynamic system, may exhibit chaotic phenomenon over some ranges of the initial conditions. The chaos in the TSS has been analyzed using mathematical and computational techniques such as phase portraits, spectral analysis, Poincaré sections, and Lyapunov exponents for planar motion (see Refs. 59 and 60) and with three-dimensional motion[61] of the TSS during the station-keeping phase.

F. Tension Control Augmented with Thrusters

Several more complex tension control models have been proposed. However, the major limitation of the tether tension control is its dependence on the gravity gradient, which is governed by the tether length.[13] Hence, for a small flexible librating tether, the tension may be quite small or even zero when the tether goes slack. To overcome this difficulty, the TSS can be augmented with a set of thrusters with an on–off strategy to regulate the tether swing during station-keeping[62] and retrieval.[13] The tension augmentation thruster is considered for the libration control of the TSS during station-keeping, assuming a constant tether tension and neglecting the tether mass and flexibility.[63] The tension control laws are even more effective when used in conjunction with the out-of-plane thrusting.[56,64] The tether-normal continuous thrusting and quasi-linear control can stabilize a more complex TSS model by accounting for the tether deformation.[65] During retrieval maneuvers, a tether reel can be used as a feedforward actuator, whereas the tether normal thrusting should be used for feedback stabilization.[66] The LQR method can be applied to derive a tracking-type feedback control law to decrease the deviation of the subsatellite from the nominal path by using thrusters.[67] Using the main satellite's thrusters as control inputs during retrieval, Pines et al.[68] stated that on–off firing of the main satellite's thrusters in the phase plane control approach leads to stable limit cycles for both the tether pitch and roll dynamics, whereas the sliding mode method results in remarkable performance through continuous thrusting. The feedback control laws based on the H-infinity control theory and using the transverse motion of the tether are successful in damping the librational motion in the presence of disturbances.[69] Stoen and Kane[70] suggested some control strategies for the TSS when its rotation rate is to be maintained constant by means of the tangential thrusters while simultaneously varying the tether length. Koss[71] discussed the tether deployment mechanism for ATEx.

In recent years, the development of small/microsatellites has received world-wide attention. Tethered microsatellite systems have also been studied. The dynamics of these systems differ from the STSS in the sense that the center of mass of the system can no longer be assumed on the main satellite. The tether mass cannot be ignored in comparison to the masses of the end satellites. The thruster control is not possible because the size/mass of the satellite forbids the installation of thrusters. With these criteria taken into consideration, the dynamics and control of these systems during deployment have been analyzed[72] using tension control based on Rupp's control law.[34] Koakutsu et al.[73] applied a tension control scheme by first designing the optimal reference trajectory of the system using a sequential conjugate gradient-restoration algorithm for a model that ignores the tether mass. A tracking law was subsequently developed.

G. TSS in Elliptic Orbit

An equilibrium state of a TSS in an elliptic orbit is a limit cycle but it is a fixed point if the orbit is circular.[74] Given an in-plane motion and a massless tether, the equilibrium and stationary states of the system and the numerical methods have been described in Refs. 74 and 75 for computing periodic motion along with its stability and domain of attraction. An increase in the orbital eccentricity leads to an increase in the size of the limit cycle, and at the critical value of eccentricity, that is, $e = 0.3$ for a particular case,[74,75] and thereafter the limit cycle becomes unstable. The final state of the deployment cannot be an equilibrium position because the eccentricity excites tether oscillations, and, therefore, some control methods are needed. A periodic solution with a period of one orbital period can be considered as the control objective.[19] The application of periodic on–off control at certain true anomalies in the orbit using a thruster installed on the subsatellite makes the librational motion of the TSS converge on a periodic solution.[19] The libration control can be achieved by other strategies described by Fujii and Ichiki[60] as well.

A uniform rate of deployment scheme with a slower deployment rate[19] or a length rate control algorithm for the deployment/retrieval[74,75] can be applied to stabilize the TSS. Ruiz and Peláez[76] described a tether deployment strategy extending Refs. 21 and 22 with the inclusion of parameters: true anomaly at the beginning of the deployment and orbit eccentricity. Beletsky and Levin[46] provided an alternate strategy for the tether deployment, whereas Bergamaschi et al.[77] analyzed the TSS-1 librational motion due to orbital eccentricity.

H. Orbital Motion and Tether Librational Motion Coupling

For the station-keeping phase, an exact solution of an in-plane motion of a TSS that ignores the tether mass and libration is obtained in terms of elliptic functions, and an approximate solution is found by applying a general method of averaging.[78] The solution to the equation that governs librational motion considering small-amplitude libration is then obtained and found to have good agreement with the numerical results. The out-of-plane librational motion of the TSS is generally small and has less effect on the orbital motion than the in-plane libration because the velocity it produces is orthogonal to the orbital velocity.[79]

I. TSS in Atmosphere

Most of the studies related to TSS in an atmosphere consider a spherical subsatellite.[80–87] In the presence of aerodynamic forces, the equilibrium configurations of the STSS assuming a rigid tether were discussed by Bergamaschi and Bonon[80] for the case of an in-plane motion in a circular equatorial orbit. It was found that, with an increase in the tether length, the effect of atmospheric drag increases, resulting in a subsatellite equilibrium position moving farther and farther away from the local vertical position. Lorenzini et al.,[82] and Pasca and Lorenzini,[83] considering a straight tether as well as flexible tether models, that is, with bending modes, found that the static equilibrium configurations of the system lie on the orbital plane for equatorial orbits in the case of the tethered Mars probe. However, a system in the presence of aerodynamic forces can be unstable due to the combined effects of tether elasticity and atmospheric density gradient.[88] In Ref. 89, the stability of the system equilibrium states is investigated analytically, and the corresponding stability criteria of the system are presented in terms of subsatellite mass, tether length, and atmospheric drag. The in-plane tether librations can be controlled by tether tension[88] or by changing tether length proportional to the in-plane libration angle.[82] Pasca and Lorenzini[84] extended the work[82,83] to include elliptic orbit. An active feedback control of the tether length is applied to attenuate the tether librational motion.[84] The stability criteria in a slightly eccentric orbit ($1.5 \times 10^{-4} < e < 1.5 \times 10^{-3}$) was found to be almost the same as those in a circular orbit.[90] Thus, the divergent TSS librational motion may be due to either a parametric resonance in equatorial circular orbits[89,91] or to a forced resonance phenomenon in elliptic or/and inclined orbits.[90] For a TSS in an equatorial orbit, the air drag acts on the in-plane libration and remains constant only if a spherical atmosphere is considered. However, for a polar orbit, both the in-plane and the out-of-plane librations are excited. In general, the atmospheric density is considered as a function of altitude only. However, the atmospheric density is different during the day from that during the night. The conclusions of Ref. 88 still hold when this is taken into consideration for the TSS in-plane motion.[92] The linear tension controller developed in Ref. 36 is effective in controlling the three-dimensional motion of the tether.[93] The problem of the equilibrium and stability of a tethered subsatellite in the presence of probabilistic aerodynamic forces was addressed by de Matteis and de Socio.[94] The control of a tethered subsatellite during deployment/retrieval maneuvers was examined by Fujii et al.[95] Including the orbital motion of the TSS along with the tether in-plane librational motion, Puig-Suari and Longuski[85] stated that the use of tethers in an atmosphere is feasible in circular/elliptic orbits when thrust is applied at the orbiter. However, in the case of an aerocapture from a hyperbolic orbit, the tether tension becomes quite large.[85] Zhu et al.[20] considered the three-dimensional TSS motion where the orbital motion is controlled using thrusters installed on the main satellite, and the librations are controlled by linear (for deployment and station-keeping) or nonlinear (for retrieval) feedback modulation of the tether tension.

III. Dynamics and Control of Two-Body TSS in the Presence of Tether Offset

In the presence of an offset between the tether attachment point and the mass center of the end satellite termed the tether offset, the satellite experiences additional moments, and its attitude motion becomes coupled to that of the tether librational motion.[96] The approaches such as tether tension, tether offset, thruster, momentum wheel, and their combinations are considered to control the attitude of the end satellites and the whole system as well.[96]

A. TSS Dynamics: Single Tether

The nonlinear terms have negligible influence on the subsatellite attitude motion during deployment and station-keeping.[97] However, these terms affect the motion during retrieval, and, thereby, nonlinear models should be considered in tether retrieval studies.[97] For the in-plane motion of a system, the amplitude and frequency of the satellite oscillations are generally found to be functions of the tether tension and satellite orbital frequency.[98] The frequencies of pitch and roll motions of the rigid platforms connected together with a rigid tether are $\sqrt{3}$ and 2 times the orbital frequency, and the yaw frequency is dependent on inertia parameters.[99] However, the system becomes unstable for certain inertia combinations.[99]

B. TSS Dynamics: Two Tethers

Misra and Diamond[100] considered three-dimensional motion of a TSS comprising a small pendulumlike subsatellite mass deployed from a main satellite such as the space shuttle through two identical extensible, massless tethers. Assuming no attitude motion of the main satellite, the two-tether system is found to have superior rotational behavior in comparison to a single-tether system, but is found to have adverse tether longitudinal oscillations.

C. Satellite Attitude Control: Single Tether

The tether tension due to gravity gradient forces can be used to control the attitude of the end satellite.[101] However, the tether tension forces the end satellite to follow the tether librations, thereby possibly resulting in parametric resonance with the end satellite's attitude.[101] A long tether can provide a large restoring torque resulting in high satellite pointing accuracy, but it is sensitive to external disturbances, whereas a short tether is better for filtering out high frequencies.[102] Bainum et al.[103] stated that feedback control of the TSS librational motion using tether tension alone is not possible and that a momentum wheel is required for stabilization. A tension controller and gyrodamper can control the attitude of a tethered remote sensing satellite system satisfactorily.[104] For deployment/retrieval assuming linearized equations of the TSS motion, velocity feedback with thrusters and momentum wheels is successful in controlling tether librations and the attitude of a plate-type space station, respectively.[105] It is found that consideration of only the rigid degrees of freedom is not sufficient because the flexible dynamics of the tether become unstable, particularly during retrieval.[106] Passive dampers have been proposed to control the flexible dynamics.[106]

The choice of tether offset has a significant effect on the system transient response.[103] A study on the dynamics and control aspects of a space platform in the presence of tether offset was undertaken by Fan and Bainum.[107] For the requirement of disturbance rejection, the motion of the tether attachment point along the roll and pitch axes is able to produce the pitch and roll control moments, respectively.[101] A precision pointing offset control algorithm for the TSS was developed using an LQR feedback law and a Kalman filter to regulate the subsatellite motion.[108] The tether offset control scheme involving time-dependent motion of the tether attachment point is successful in damping the momentum of a main satellite having initial momentum.[109] The effectiveness of this scheme was validated by Modi et al.[110] through a ground-based experiment as well as a numerical simulation. In a subsequent study,[111] three different control strategies: thruster control, tension control, and offset control, as well as their combinations, were compared, and it was found that the thruster-offset hybrid controller is the most effective in damping disturbances.

Controllers for the TSS attitude and vibrational motion were designed by Pradhan et al.[112] using a feedback linearization technique and a robust linear-quadratic-Gaussian/loop transfer recovery (LQG/LTR), respectively. The tether offset scheme was found to be effective in simultaneous control of the platform and tether pitch motion for a shorter tether.[112] For a vertical interferometric synthetic aperture radar tethered altimeter comprising two space platforms of comparable mass,[113] the three-axis attitude control during the station-keeping phase is possible using a conventional reaction wheel to control the yaw difference between the platforms and by slightly moving the tether attachment point to damp pitch and roll high-frequency oscillations. Pradhan et al.[114] applied momentum wheels for the platform libration control and an eigenstructure assignment, along with an offset controller for vibration suppression. A controller design using a graph theoretic approach was considered by Modi et al.[115] For a smaller end satellite such as SEDS's payload,[116] a long, rigid appendix at the tether attachment point is effective in stabilizing the satellite's attitude. Grassi and Cosmo[117] applied rigid booms and fins for drag stabilization, a tether offset control for the payload attitude control, and a thruster for the tether librational control. The case where one of the two tether attachment points suddenly stops was considered by Grassi et al.,[118] extending previous work.[113]

D. Satellite Attitude Control: Two/Multitethers

The concept of pulling on the tethers proposed by Banerjee and Kane[119] can be used to control the pitching stability of an auxiliary space platform connected by two tethers to a space station. Their simulations for the assumed specific system with short tethers, that is, 100 m long, demonstrated that the uncontrolled TSS dynamics is unstable. This was perhaps instrumental in their pursuing the closed-loop tether tension variations for auxiliary space platform attitude control. However, the linearized pitching stability analysis undertaken by Kumar[120] brought about a simple tether length criterion that explained not only the instability of the system, but also suggested the existence of a critical tether length limit above which the system becomes unstable. Three-dimensional attitude motion of the main satellite by two tethers was considered by Ciardo and Bergamaschi[121] using linearized equations of motion and without tether tension variations. It was found by Kumar and Kumar[122] that the DeBra–Delp gyric stability disappears and that a positive value of inertia parameters K_2, corresponding to inherent system yaw stiffness, is essential for the stability of the TSS. However, the tether attachments enable one to practically do away with the restriction on the choice of the other inertia parameter K_1, thereby substantially augmenting the parametric zone of the main satellite pointing stability without a tether. The system pointing stability characteristics may also be sensitive to changes in the values of other system parameters. Similar findings were reported by Ashenberg and Loreinziini[102] for a single-tether system. To achieve the benefits of the single- and two-tether configurations regarding their dynamic characteristics, a kitelike tether configuration was proposed by Kumar and Yasaka.[123] A linearized stability analysis and numerical simulation of the TSS established the feasibility of the proposed configuration.

The TSSs described so far have a weight penalty associated with the tethered subsatellite mass. To do away with the weight penalty, the main satellite itself can be considered to be made up of two halves so that each one of these plays the role of a subsatellite for the other. The problem of pitch attitude motion of both of the connecting satellites was considered by Kumar and Kumar[124] and later extended to the three-dimensional attitude motion of a dual satellite.[125] Three particular tethered configurations involving cases with parallel tethers, a parachutelike conical tether layout, and a single-tether connection were investigated. Among these, the parachute tether layout appears to provide relatively superior attitude performance, and tether lengths on the order of a few meters are found adequate to impart a high degree of three-dimensional librational stability to small or even medium size dual satellites. A detailed description of the system along with numerical simulation and linearized stability analysis is presented in Ref. 126. Colombo[127] proposed a space station consisting of two large massive platforms joined in a gravity-gradient stabilized configuration by a number of parallel tethers several tens of kilometers long. A simplified linearized analysis considering a space shuttle and a much smaller tether connected subsatellite mass led to the development of design guidelines for pitching stability of the space station.

E. Satellite Attitude Maneuver

The problem of attitude maneuvers of a satellite was undertaken by Kumar and Kumar[128] considering the system described in Ref. 120. The pitch attitude maneuver of the main satellite is accomplished using an open-loop control law for the variation of tether lengths on the order of twice the tether offset. Bernelli-Zazzera et al.[129] presented roll attitude maneuvers of a space station equipped with two massive tethers, one toward the Earth and another in the opposite direction. Their approach, however, requires long tethers and large variations, as well as simultaneous changes in the tether offsets. The pitch and roll attitude maneuvers were later considered by Kumar and Kumar.[130] The open-loop control law for varying only the lengths of connecting tether lengths has been developed for executing arbitrary pitch and roll attitude fixed or chase-slewing maneuvers. This analysis was extended to attitude maneuvers of dual satellites.[131] The application of only tether offset variations for the orientation control of the main satellite with a single tether was studied by Modi et al.[132] using a Lyapunov control strategy. Afterward, Kumar and Kumar[133] proposed a simple open-loop tether offset control law for attitude maneuvers of both satellites connected by a relatively short tether.

F. TSS in Elliptic Orbit

In the presence of orbital eccentricities, typical satellite–tether configurations are outside the orbital eccentricity resonance region.[102] The pitch attitude control of a satellite in an elliptic orbit using two tethers was considered by Kumar and Kumar.[134,135] An open-loop control law for tether length variations was proposed using an approximate analytical approach that seeks to make use of the tether tension moment to eliminate the harmonic satellite pitching excitation induced by orbital eccentricity. The augmentation of the proposed open-loop control law with the feedback results in high-attitude precisions. This analysis was extended to the three-dimensional attitude control of the main satellite.[136] Ashenberg and Lorenzini[137] used a single tether to control the main satellite's attitude in small eccentric orbits, applying a combination of Floquet transformation and sampled state periodic hold feedback control to vary the tether offset. The tether offset to control the satellite attitude was also applied by Kumar.[138] This analysis was later extended to the attitude control of the end satellites using the tether length variation in a multitether system[139] and using the tether offset variation in a single-tether system.[140] The feasibility of using satellites in nonequatorial 24-h circular orbits for communications by applying tethers was discussed by Kumar and Kumar.[141]

G. TSS in Atmosphere

In the presence of an atmosphere, the attitude of the subsatellite along with tether librational motion may become unstable even without tether offsets in certain cases.[142] The passive stabilization of the subsatellite using aerodynamic forces by means of fins attached to a boom mounted on the subsatellite has been studied by many researchers.[35,143] Santangelo[143] discussed active and passive controls of the three-dimensional attitude motion of the subsatellite using a reaction wheel and aerodynamic equipment without considering the tether flexibility and aerodynamic forces on the tether. For a successful atmospheric tether mission, the altitude of the subsatellite or the probe can be controlled by varying tether length,[82] using a hypersonic wave rider,[144] and applying a lifting probe with movable tether attachment.[145,146] Keshmiri and Misra[147] proposed lifting probes to increase the system stability. The range of equilibria for various tether lengths and attachment point locations for a Mars sampling mission was obtained by Biswell and Puig-Suari,[145] and in a later investigation[146] it was found that the atmospheric TSS always contains at least one unstable mode that needs to be controlled. The system is controllable using a linear control system that considers the probe attachment point motion and thrust at the orbiter. Alternatively, the system is fully controlled using only the probe attachment point motion to keep the thrust at the constant equilibrium value. Biswell and Puig-Suari[148] further applied a lifting probe with a movable tether attachment point for the attitude control of the probe in the Earth's atmosphere. The successful aerocapture for planetary missions is possible even in the presence of the system and environmental uncertainties.[149]

H. Spinning TSS

The damped gyroscopic natural modes of a spinning TSS with flexible booms were studied by Vigneron et al.[150] The divergent nutation of the aft payload of OEDIPUS-A is found to be caused by the tether, and the boom flexibility is not a major factor. The nutation modes of the OEDIPUS-C payload are stable at its flight spin rate of 0.09 Hz. However, the system is susceptible to boom-associated structural instability at spin rates above 0.26 Hz. For the analysis of the attitude dynamics of the spinning TSS, Tyc and Han[6] considered tether tension exerted on the end bodies and included the additional energy dissipation. In a subsequent study, Tyc et al.[151] considered tether motion in the modeling of the system dynamics and derived closed-form conditions for the asymptotic stability of the spinning TSS using the linearized equations. The tether spin is found to have significant effects on the dynamics and stability of the spinning TSS. In another study, Tyc and Han[152] considered a system model incorporating bending of the tether at the tether root. Interestingly, the effects of the tether root bending lead to the same dynamics anomaly observed in the OEDIPUS-A mission when the aft payload exhibited an unexpectedly rapid and large divergence of the coning angle. The tether mass and boom flexibility are found to have a destabilizing effect, whereas the tether tension and the bending effects at the tether root have a stabilizing tendency.

I. Ground-Based Experiment

Gwaltney and Greene[153] obtained results of a ground-based experiment of the out-of-plane libration control scheme (see Ref. 45) and the corresponding equivalent tension control law with tether length and length rate as feedback, in agreement with the numerical simulations. Applying an exponential tether length variation with respect to time in the presence of a small control input, Higuchi et al.[154] found that the control can suppress the divergent vibration of a retrieving tethered satellite. A demonstration of the tether offset control strategy was shown by Kline-Schoder and Powell,[155] Modi et al.,[110,156] and Pradhan et al.[157] Bernelli-Zazzera[158] presented an experimental verification of active control of the in-plane pendulum oscillations and tether bobbing of the TSS by boom rotation. The out-of-plane oscillations are not controllable. In two parallel investigations[159,160] on the spinning systems related to the OEDIPUS missions, the analytical predictions of critical speeds based on linearized analyses were found to be in close agreement with the experimental observations. However, some discrepancies observed in the theoretical model results seem to suggest the need to retain the nonlinear terms in the stability analyses. Schultz et al.[161] considered a horizontally suspended tether to carry out a ground test for the Bistatic Observations with Low-Altitude Satellites (BOLAS) mission.

IV. Dynamics and Control of Multibody TSS

The literature on the multibody TSS considering point masses is reviewed first, followed by papers considering finite masses multibody TSS.

A. Multibody TSS: Point Masses

The in-plane dynamics of three-body tethered systems in a circular orbit around the Earth has been studied by several authors, including Liu,[162] Lorenzini,[163] and Misra et al.,[164] considering point masses and massless tethers. The tethers are treated as rigid except by Lorenzini,[163] who considered tether longitudinal oscillations. For fixed tether lengths, there are four equilibrium configurations[164]: one along the local vertical, a second along the local horizontal, and for certain combinations of parameters, the third and fourth being configurations in which one tether is along the local vertical, whereas the other is inclined to the local vertical. Among these configurations, the one along the local vertical is the only stable configuration. The frequencies of tether librational motion around the stable configuration and the corresponding mode shapes are found. Note that large librational motions may occur during a cargo transfer. An extension to the three-dimensional motion of the system was undertaken by Sarychev[165] and Amour et al.[166] The 11 classes of equilibrium configurations, 4 of which lie in the orbital plane, were found.[166] Two equilibrium configurations with three masses on the local vertical are marginally stable, whereas the triangular configurations are unstable except for some systems with a small middle mass.[166] For the local vertical equilibrium configuration, Decou[167] examined a three-body TSS for interferometric application. Analyzing the dynamics of the four-body tethered system called the tether elevator/crawler system (TECS), consisting of two platforms, the space station, and an elevator, Cosmo et al.[168] considered the in-plane motion of the system along with the damping of librational motion and longitudinal tether oscillations and obtained the eigenvalues and eigenvectors of the system, whereas Lorenzini et al.[169] assumed the three-dimensional motion of the system considering the J_2 perturbation due to gravity, air drag, and thermal effects. Misra et al.[170] extended the work[164] to the three-dimensional motion of an *N*-body TSS. The in-plane and out-of-plane librational frequencies of each tether in this system are found to have the same values as those observed in a single tether of a two-body TSS. The reel rate laws using linear pitch rate and quadratic roll rate feedback are successful in controlling the motion of the three-body system and the four-body system like TECS during deployment, retrieval, or station-keeping. The tether elasticity and its mass in the *N*-body TSS were later considered by Keshmiri et al.[171]

B. Multibody TSS: Finite Masses

Lavagna and Finzi[172] investigated equilibrium and stability of two system configurations: a central extended body and two point masses connected to it through booms and two point masses attached with booms with an extended body at the extremity of the system. The 12 basic equilibrium configurations were found, and, among these, only 1 configuration was stable. A parametric stability analysis of the system was undertaken later.[173] The control of a system comprising of a space station of finite mass, an elevator, and the end platform was examined by Modi et al.[174] using a tether offset and thruster, along with a momentum gyro that controls the space station's attitude. Three bodies of finite masses connected through tethers were considered by Kumar,[175] and the tether offset control strategy was proposed to control the motion of the TSS in elliptic orbits. Kalantzis et al.[176,177] extended previous work (see Ref. 112) to an *N*-body TSS, deriving the equations of motion of the system using an order-*N* Lagrangian procedure. The spin motion of the system about an arbitrary axis (cartwheeling), as in the case of the Bistatic Canadian Experiment on Plasmas in Space (BICEPS) or OEDIPUS-A/C Missions, is also included in the model.

C. Multibody TSS in Atmosphere

Assuming three point masses and neglecting the orbital perturbation due to atmospheric drag, Ashenberg and Lorenzini[178] found that a system of two probes attached to a massive orbiter through an inelastic and massless tether has an amplitude ratio of 4:1 between the pitch angles of the lower and upper probes and that this ratio becomes larger at lower altitudes. The small eccentricities results in bounded librational oscillations. Takeichi et al.[179] considered a system of four small subsatellites of finite sizes and a massive main satellite connected by a flexible tether. The libration of the total system is found to diverge due to the atmospheric drag, and the total system later begins a tumbling motion.

V. Tether Models and Modes of Vibration

Because of the complexity of TSS dynamics, several simplifying assumptions are made while modeling the system. Various tether models have been considered depending on the emphasis on the objective of the analysis. As the fidelity of the model increases, so does the complexity of the analysis and the controller. In comparison to the end satellite attitude motion and tether librational motion, the control of both longitudinal and transverse vibrations of the tether is not easy because it may get excited to unacceptable levels during deployment and, in particular, during retrieval, due to Coriolis excitation even without initial disturbances.[13] Strategies such as tether tension/length control, tether length rate control, tether offset control, and passive tether damping, that is, viscous damping, besides the use of thrusters, have been applied to attenuate the tether vibrations.[96] The details of various tether models and the modes of tether vibration are discussed starting with the tether model.

A. Tether Model

The simplest way to model the tether is to treat it as a rigid, massless rod.[34,38,45,48] When this type of model is used to describe the rigid-body motion of the system, the tether bending and stretching are ignored. To include the effect of the first longitudinal mode, the tether can be represented by an extensible, massless rod. In the second type of model, the tether is represented by a sequence of elements, such as beads connected by rigid massless rods,[144] beads connected by massless springs,[180] lumped masses connected by massless springs–dashpot,[116,117,169] a series of rigid rods,[67,181] or finite elements.[182] These models allow for the tether curvature and, consequently, are more realistic than those that preclude bending. To obtain high fidelity, a sufficient number of elements must be used. In the case of the tether being modeled as massless springs and point masses or beads connected in series, the system will more closely represent a continuous tether as the number of beads is increased. One advantage of using the bead model is that the effect of geometric nonlinearity/tether curvature is duly accounted for. However, the computational time and the cost increase rapidly as the number of beads is increased. For simulation of the tether deployment or retrieval, there are two approaches: the fixed number-of-beads approach and the variable number-of-beads approach. In the former approach,[183,184] the number of beads is constant, and the mass of the beads and the length between the beads are varied uniformly to correspond to the mass and length of the deployed portion of the tether. Steiner et al.[182] described the appropriate convective terms required to distribute the tether mass and stiffness properly using a domain mapping to a fixed spatial region, followed by a restating of the variational principle in the new domain. In the variable number-of-beads approach, the mass of each bead and the undeformed length between beads are treated as constant. The deployment/retrieval is simulated by continually adding/subtracting the beads at discrete intervals as the tether length is varied. This approach was used by Banerjee[183] to simulate both the extrusion of beams and the deployment of tethers in which the elastic extension between beads is not taken into consideration. Leamy et al.[33] found it to be more computationally efficient to consider the deployment starting with a near-zero initial tether length. Kim and Vadali[184] used this approach with elastic springs as links.

For atmospheric tether missions, Puig-Suari et al.[87] extended the analysis (see Ref. 85) to include a flexible tether, considering it as a chain of linked rigid rods with the end-body masses as particles. The flexible tether model could provide correctly the magnitudes of the tether normal and tension forces and the tether shape during atmospheric fly-through. This model is further extended to a three-dimenisonal hinged-rod model,[185] considering the tether as a collection of hinged rigid bodies connected by springs and dampers and considering the end bodies as rigid bodies with three-dimensional attitude motion. With this model, considerably fewer elements are required in comparison to the number of beads in the bead model for similar results. Warnock and Cochran[186] accounted for variation in flow regimes where atmospheric tethers might operate, and the drag acting on the tether was determined using aerodynamic coefficients that are dependent on the rarefaction of the flow characterized by its Knudsen number.

In yet another class of models, a continuous massive tether is considered. The tether may be elastic[65] or inextensible. To deduce practical information from this kind of analysis, the equations of motion are often simplified by accounting only for the principal vibrational modes. The three-dimensional vibration of the tether was investigated by Misra et al.[187] using the Ritz–Galerkin method to consider the effect of geometric nonlinearity on fundamental modes of longitudinal and transverse vibrations while ignoring the tether in-plane and out-of-plane librational motions. The geometric nonlinearity was found to have a stiffening effect against lateral vibrations. An approach similar to that in Ref. 187 was adopted by Liu and Bainum[40] to obtain the equations of motion for their TSS model, ignoring the geometric nonlinearity and considering the steady-state value of the tension instead of the actual tension in the equations for the lateral vibrations. For the analysis of tether oscillations, the linearized equations of motion are also considered.[188,189]

By comparison of the numerical simulation results obtained from discrete and continuous tether models,[184] it was found that the tether discrete bead model represents the realistic behavior of the system. Keshmiri and Misra[190] considered a hybrid bead/continuum model to study TSS dynamics. The tether model presented by Biesbroek and Crellin[191] considering the tether as a set of point masses (beads) connected by straight, inextensible, and massless lines results in short simulation time apart from showing good agreement with a sophisticated continuous model. Bergamaschi et al.[192] found that the results of the mathematical models implemented in two different general purpose computer codes, the SKYLINE advanced tether simulator and the tether dynamics simulation package, compare well with the spectra of the accelerometric package mounted onboard the first TSS-1 mission. Beletsky and Levin[46] and Glaese[193] provided different TSS dynamics simulation packages. A review on measurement techniques and instrumentation for the TSS was presented by Brown et al.[194]

B. Tether Modes of Vibration

A spectral analysis of the frequencies of the free vibrations of the TSS-1 mission during the station-keeping phase was conducted by Bergamaschi and Catinaccio[195] and Bergamaschi et al.[196,197] using the linearized equations with the averaged longitudinal stress. The measured frequencies of transverse tether oscillations and satellite roll–pitch were found to match well with the theory, as well as with several combination tones of the fundamental modes that are found to be present in the spectra. By analysis of the nonlinear free periodic transverse oscillations of the TSS,[198] the frequencies and mode shapes of the oscillations were found to be dependent on the amplitudes. The frequencies of the in-plane and out-of-plane vibration modes are very close, and the slight differences between them were attributed to the different influences of centrifugal and gravitational forces on the tether in the two planes. However, the control of the longitudinal vibrations of the tether can arrest the growth of the in-plane transverse vibrations during retrieval.[187] The laws of retrieval proposed in Ref. 187 were extended by Djebli et al.[199] The fast laws[199] result in a good system response during the retrieval phase if they are combined with the simple laws.[13] The mixed procedure involving the simple sinusoidal law gives the best transverse vibrations response as compared with the simple linear/exponential laws. The bending oscillations of the tether were studied by Levin.[200] He and Powell[201] considered damping of the longitudinal and transverse vibrations along with the skip-rope motion of the tether due to its material properties, neglecting the tether librational motion. The tether internal friction does, however, affect its librational motions.[202] A theory of long-term evolution of librational motions was presented by Levin.[202] The 5:4 resonance between the out-of-plane and the in-plane librations is considered to be responsible for unusually rapid decay of the out-of-plane librations during the first two months of the TiPS flight. Long-term modeling of the tether dynamics was also performed by Misra et al.[203] for the same TiPS mission.

The coupling of tether lateral vibration and attitude motion of the subsatellite was investigated analytically by Bergamaschi and Bonon,[204] assuming a small amplitude of subsatellite attitude motion during the station-keeping phase. In the presence of aerodynamics forces, the tether longitudinal oscillations with frequencies close to those of the subsatellite pitch motion can diverge for an energy transfer from the subsatellite to the tether, keeping tether librational motion almost unaffected.[205]

C. Multibody TSS

Kumar et al.[206] determined natural frequencies of the in-plane transverse vibrations for a three-point mass body system connected through two tethers. Lorenzini[163] proposed a strategy applied to a three-body system for controlling longitudinal oscillations using passive spring–dashpots tuned to the natural frequency of each tether segment. Keshmiri et al.[171] considered longitudinal and transverse vibrations of the tethers of a three-body and four-body TSS. A segmented-tether model is applied to obtain higher frequencies of the system. The structural damping is found to affect tether longitudinal oscillations significantly, whereas transverse oscillations remain unaffected. An order-*N* Lagrangian algorithm was presented by Kalantzis et al.[177] for an *N*-body TSS of finite masses connected in series by flexible tethers. The elastic deformations of tethers are discretized using the assumed mode method with the inclusion of foreshortening effects due to geometric stiffness.

D. Spinning TSS

The tether elastic oscillations of a system spinning about the orbit normal were considered by Quadrelli and Lorenzini.[207] Luo et al.[208] analyzed the aspects of tether oscillations in a system spinning about the tether longitudinal axis as in the OEDIPUS-A mission. The resonance and stability conditions of the proposed system were obtained. This study was extended by Min et al.,[209] and it was concluded that the linear analysis can predict the resonance frequencies and mode shapes of vibration of a stretched string; however, phenomena such as jump response, sub/superharmonic response, saturation, and amplitude-modulated motion are explained by introducing nonlinear terms into the formulation. The tether damping in the longitudinal modes drives the steady state to the limit steady state of the transverse mode.

VI. Tether Applications

Although various applications of the TSS have been envisaged and proposed in the literature,[3] the pertinent literature on orbit transfer, formation flying/artificial gravity, and aeroassisted orbital maneuvering are only reviewed.

A. Orbit Transfer

Colombo et al.,[210] Bekey and Penzo,[211] Carroll,[212] and Pearson[213] showed that tethered systems provide significant impulse savings for transfer missions from circular orbits. Kyroudis and Conway[214] stated the advantage of an elliptically orbiting tethered dumbbell system for satellite transfer to geosynchronous altitude. The effects of various tether deployment schemes, as well as of out-of-plane libration on the payload orbit raising, were studied by Kumar et al.[16] Tumble orbit transfer for spent satellites was proposed by Yasaka.[215] Bekey[216] and Kumar[24] showed the advantage of payload deployment by reusable launch vehicles using tethers. Lorenzini et al.,[217] Ziegler and Cartmell,[218] and Kumar et al.[17,219] analyzed and discussed a spinning tethered system. Payload boosting from a low Earth orbit to a geosynchronous transfer orbit was also discussed by Taylor.[220] Spinning tethers for rapid orbital plane change were proposed by Tillotson.[221] The findings of some of these research activities are summarized as follows.

First, in the case of the starting orbit being circular, for example, end-mass 1 (m_1) facing toward the Earth and end-mass 2 (m_2) facing outward at the time when they are released, the maximum decrease in the altitude of m_1, as well as the maximum altitude gain of m_2 after one-half an orbit, occur simultaneously when the libration angle is zero on the forward swing and are obtained considering terms up to $\mathcal{O}(\hat{r}_i^2)$ as

$$\Delta H_i = [7 + 4\delta + 30\hat{r}_i + 2\hat{r}_i(18 + 5\delta)\delta]r_i, \qquad i = 1, 2 \tag{1}$$

where

$$r_i = (-)^i[(m_k + m_t/2)/M]L \quad \text{if} \quad i = 1, k = 2, \quad \text{if} \quad i = 2, k = 1 \tag{2}$$

If the end masses are equal and the distance between them is $2L$, that is, $r_i = (-)^i L$, Eq. (1) reduces to the relation obtained by Ziegler and Cartmell.[218] If $m_1 \gg m_2$ is assumed and terms up to $\mathcal{O}(\hat{r}_i)$ are considered, then the relations for swinging and spinning tether systems can be found.[217] To obtain the relation in the case of a hanging tether,[211] the variable $\delta = 0$ is substituted in Eq. (1). An alternate relation of the apogee gain of ΔH_2 is obtained for swinging release assuming $m_1 \gg m_2$, and the tether and its end mass remain in the original circular orbit[3]:

$$\Delta H_2 = \left(7 + \sqrt{48}\sin\beta_{\max}\right)L \tag{3}$$

where $\beta_{\max}$ is positive for prograde and negative for retrograde rotation.

For a spinning tether system, it is possible to achieve altitude gains greater than $14L$ (Ref. 217) and $25L$ (Ref. 211). However, note that the perigee gain is only up to L. To attain high perigee gain, a two-cut procedure is proposed.[222] Here, the tether departs with the payload at the first cut. Then, close to the apogee, the tether is cut next to provide additional raising of the perigee. However, the perigee and lifetime increase from the second cut are limited because a typical tether having low mass can transfer little momentum at the second cut, and the TSS libration with a free end is unstable. To overcome these problems, it is better to leave the mass attached to the free end of the tether.[223] This modified procedure results in higher orbit and longer satellite lifetime even for small values of the attached mass. In a low Earth orbit, the end mass can even double the one-cut lifetime. A sensitivity analysis for such a two-cut procedure was conducted later.[224] Kumar et al.[17] considered a tether retrieval for the orbit transfer, and state that if the tether length is decreased by ΔL, then the altitude gains of the two connecting masses m_1 and m_2 are

$$\Delta H_i = -\left(\frac{m_k + m_t/2}{M}\right)\left[3 + \frac{4(1+\dot{\beta}_0/\Omega)}{(1-\Delta L/L)^2}\right](L - \Delta L)$$

$$i = 1, 2, \quad \text{if} \quad i = 1, k = 2, \quad \text{if} \quad i = 2, k = 1 \qquad (4)$$

Second, in the case of an initial elliptic orbit, the maximum altitude decrease of m_1 occurs at the apogee, and the maximum altitude gain of m_2 occurs at the perigee point, respectively, for zero libration angle on the forward swing; these are obtained taking the term up to $\mathcal{O}(\hat{r}_i)$ and $\mathcal{O}(e)$ as

$$\Delta H_{a1} = r_1[7 + 4\delta(1-e) - 20e]$$

$$\Delta H_{p2} = r_2[7 + 4\delta(1+e) + 20e] \qquad (5)$$

Spinning tethers are proposed for the transfer of the payload from low Earth elliptical orbits to geostationary Earth orbit and to the moon and Mars.[217,225,226] In these studies, it was found that it is possible to obtain velocity gains between 0.6 and 2 km/s for orbit eccentricities and tether lengths from the system's center of mass to the payload in the range $0.1 \leq e \leq 0.66$ and $39 \leq L \leq 400$ km, respectively. However, Crellin and Janssens[227] showed that the maximum velocity gain is only 102.8 m/s for a tether of 100-km length and an orbital eccentricity of 0.41. Similar results were obtained by Ziegler and Cartmell.[228] The two-stage spinning tether system was analyzed by Lorenzini et al.[217] and later extended to multistage spinning tether systems (up to four stages) by Yamagiwa and Sakata,[229] considering performance optimization of the system in relation to the number of stages and tether lengths. An analysis of the two-cut procedure in circular orbits[222] was extended to elliptic orbits by Ruiz et al.,[230] and the stability of the system including transverse oscillations of the tether with a free end in an elliptic orbit was studied. The influence of the small end mass left after the first tether cut on the orbit transfer was later investigated.[231] Stuart[232] considered the problem of a tether-mediated rendezvous and proposed a guidance and control algorithm. A tether sling shot assist for outer-space exploration was considered by Puig-Suari et al.[233] and Lanoix and Misra.[234] Hypersonic airplane space tether orbital launch (HASTOL) architecture for payload orbital transfer was also studied.[235]

An alternate method of propelling the payload using tethers is based on deployment and retrieval of a length of tether exploiting the gravitational force.[236–241] If the tether is retrieved at the perigee of the orbit and deployed at the apogee, and this process of deployment and retrieval continues, the TSS moves to increasingly higher eccentric orbits.[236] Beletsky and Levin[46] proposed this novel method and introduced the name gravicraft to refer to a TSS that is powered by actively controlling the dimensions of an extended body in orbit. Breakwell and Gearheart[237] presented an alternate proposal exploiting the oblateness of the gravitational source to generate height. A height gain of 100 m/year was found for the system orbiting the Earth. Studies on this pumping mechanism were conducted by Martinez-Sanchez and Gavit,[238] Landis and Hrach,[239] Landis,[240] and Anderson and Hagedorn.[241] Expansion of the geostationary orbit resource by tethered chain satellites was considered by Yasaka and Hatsuda[242] and Kumar.[243] The effective rates of altitude gain above the Earth demand eccentric orbits and tether lengths on the order of several thousand kilometers. Some of these techniques have been summarized in Ref. 244. Gratus and Tucker[245] showed that by suitably varying a tether length of 50 km, the TSS can rise at 300 m/h in low Earth orbit.

B. Formation Flying/Artificial Gravity

Farley and Quinn[246] discussed tethered formation configurations for a large aperture and interferometric science. A proposal of a tethered Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) mission flying at the sun–Earth L_2 Lagrange point was put forward by Quinn and Folta.[247] Wong and Misra[248] analyzed the dynamics of a four-body tethered satellite system near the sun–Earth L_2 Lagrange point, determining its equilibrium configurations and its stability about the equilibrium configurations. Colombo[249] and Farquhar[250] proposed the concept of stabilizing a TSS near a collinear libration point of the Earth–moon system by varying the tether length. A nonlinear control law was applied by Colombo[249] to vary the tether length with a view to stabilize the TSS at the collinear libration point, whereas Farquhar[250] stabilized the TSS by varying the tether length in a way that takes advantage of the nonlinearities in the modified potential field near the libration point. Considering the motion in the plane of the motion of primary bodies, Misra et al.[251] found the librational frequencies of the tether as approximately 4Ω at L_1, 3Ω at L_2, and $\sqrt{3}\Omega$ at the other Lagrangian points. Bombardelli et al.[252] analyzed the pointing dynamics of a three-body online tethered interferometer orbiting in an Earth-trailing, heliocentric orbit. Reconfiguration of the interferometer was achieved by varying the baseline length from 100 m to 1 km. Polzin et al.[253] stated various propulsion options including a tether for a terrestrial planet finder mission. For synthetic aperture radar Earth observations, Quadrelli[254] described a general simulation model to predict the dynamics and control performance of formations of a two-body tethered system in a heliocentric orbit, as well as in a low Earth orbit (LEO). The effect of distributed flexibility arising from rod and string models on the dynamics of an orbiting formation was later investigated.[255] DeCou[256–258] studied the dynamics of a rotating triangular formation of three tethered satellites located at the vertices of a triangle with the spin rate of the formation being larger than the orbital rate for a geocentric astronomical observation mission. The spin axis of the formation is intended to remain inertially fixed. Tragesser[259] considered two cases, the first being the cylindrical case in which the plane of the formation is in the orbital plane and the second termed a conical case in which the spin axis traces out a cone with the Earth at the center of the base of the cone. For the cylindrical case, a spin rate below 1.375Ω is observed to exhibit unstable behavior for long simulation times, whereas in the conical case all spin rates produce unstable motion. Williams and Moore[260] examined a rotating tethered satellite system in LEO for an Earth-oriented formation and studied the dynamics of a three-dimensional configuration in which the satellites are arranged in a ring the plane of which is perpendicular to the nadir direction, with two anchor bodies that provide a gravity gradient restoring moment. The stability of the same three-dimensional configuration[260] was investigated by Tragesser and Tuncay[261] for the off-nadir (but still Earth-facing) orientation of the Likins–Pringle conical equilibria. Kumar and Yasaka[262] considered the general formulation of the rotating formation of a system comprising three satellites connected by flexible tethers and moving in an elliptic orbit. The different masses of the satellites and different tether lengths connecting them are included in the formulation. Interestingly, when three satellites are of equal masses, the minimum value of spin rate for steady-state system motion in the orbital plane is just one-half of the orbital rate, that is, 0.58Ω. The effects of tether deployment and retrieval on the system dynamics were also investigated.[262] Kim and Hall[263] applied asymptotic tracking laws based on input-state feedback linearization to the system. The thrust levels are found to decrease significantly with tether length control. For the triangular formation of three satellites, Tan and Bainum[264] considered two of the three satellites to be connected by a tether and stabilized along the local vertical, whereas the station-keeping of the third satellite with respect to the tethered satellites was accomplished using the method[265] they had previously proposed. For a three-dimensional observation mission, other TSS configurations have been proposed.[264]

Bainum and Evans[266] studied the effects of gravity gradient on the motion of a two-body rotating tethered system, considering the attitude dynamics of the tether along with the attitude dynamics of the end bodies. However, their study was confined to the linearized equations of motion and consideration of first-order gravity gradient effects. In another related study undertaken by Quadrelli and Lorenzini,[207] J_2 perturbations and atmospheric drag are considered, whereas the end bodies are treated as point masses. The problem of vibration control in tethered atrificial gravity spacecraft was analyzed by Thornburg and Powell.[267] Mazzoleni and Hoffman[268] presented a survey on tethered artificial gravity spacecraft and discussed the Tethered Artificial Gravity Satellite Program (TAG). They investigated a two-body tethered system that is to be boosted into LEO, deployed, and then spun up to provide gravity; they consider a simple model of the system including pitching motion of the end bodies.[269] The dynamics of the TSS stabilized by rotation were studied by Dranovskii et al.[270] Kumar and Yasaka[271] analyzed the three-dimensional motion of a rotating linear array tethered system comprising two/three satellites with consideration of the attitude dynamics of the tether connected satellites. Tension and tether offset control schemes are used to achieve satisfactory system performance during deployment/retrieval maneuvers. Change of the plane of rotation of the system for targeting was considered by Bombardelli et al.[272] The lateral vibrations of the system and their damping were later analyzed.[273]

C. Aeroassisted Orbital Maneuvering

The aeroassisted orbital maneuvering methods involve aerobraking, aerocapture, and aerogravity assist maneuvers. Studies on the aerobraking tether have been undertaken by many researchers.[80,82–84,147,186,212] A demonstration of the physical feasibility of using aerobraking tethers was presented by Puig-Suari and Longuski[85] and Puig-Suari et al.,[87] applying the characteristics of a tethered vehicle described by Lorenzini et al.,[82] which was originally intended for a circular orbit about Mars. It was found that the orbiter altitude could be maintained above the sensible atmosphere during the aerobraking maneuver. The TSS can achieve aerocapture for specific closest approach flyby attitudes ranging from an orientation that is locally vertical (called the vertical dumbbell maneuver[87]) to an orientation that is locally horizontal (termed the drag chute maneuver[87]). The TSS is designed for aerobraking at the atmosphere-bearing planets (i.e., Venus, Earth, Mars, Jupiter, Saturn, Titan, Uranus, and Neptune) of the solar system using design rules of thumb and considering vertical dumbbell maneuvers.[86] It was found that the nominal tether mass is significantly lower than the propellant mass required to achieve aerocapture.[86] Even greater tether mass reduction can be obtained by considering the optimum tether mass and the resulting aerobraking maneuver that is midway between the vertical dumbbell and drag chute maneuvers.[274] However, because the probe has smaller area, the majority of the deceleration of the system is provided by the tether itself, and, therefore, to increase the probability of successful aerocapture, the mass of the tether must be increased significantly.[149] A lifting probe with a movable attachment can place the orbiter into the desired final orbit on the first pass with a smaller and less massive probe.[146,275] For the collection of dust using the TSS, an elliptic orbit with the periapsis in the latitudinal region of high dust density reduces the propellant consumption significantly[84] as compared to the circular orbit case.[82,83]

VII. Conclusions

A vast amount of literature is available on TSS dynamics stating various control strategies validated by numerical simulations and, in some instances, by ground- and space-based experiments. For beginners to understand TSS dynamics, some of the papers that should be read initially are highlighted. The handbook[3] explains the basic concepts of TSS dynamics very well, and it should be read first followed by the review paper[13] that deals with the various aspects of TSS dynamics. This handbook[3] and paper[13] will certainly provide beginners the necessary fundamental background on the subject. The paper by Barkow et al.[29] will also lend understanding of the various laws of deployment. A recent paper by Misra[14] presents an excellent overview of TSS dynamics. To learn about TSS dynamics in depth, one should refer to the monograph by Beletsky and Levin.[46] On TSS dynamics in the presence of offsets, the paper by Modi et al.[111] should be read because they analyze the system thoroughly with applications of various control options. The paper by Biswell and Puig-Suari[148] effectively conveys the system dynamics in the presence of aerodynamics forces. For spinning TSS and multibody TSS, one should refer to Refs. 152 and 171, respectively. To learn about tether models, the paper by Kim and Vadali[184] should be read first, followed by the paper by Biswell et al.[185] Concerning vibrations issues of nonspinning TSS and spinning TSS (OEDIPUS), one should refer to Refs. 187 and 209, respectively. After reading these principal papers, one can read other references in the order they have appeared in this paper because they have been described in increasing order of system complexity. These are just broad guidelines, however, and these references may be consulted as per the reader's choice.

Although significant advancements have been made in the understanding of TSS dynamics, there remain many challenging problems yet to be explored. Formation flying using tethers is one interesting area of research. In rotating formations, various problems need to be solved. They are deployment/retrieval control strategies, tether vibration issues, and the maintenance of formations that are not in the orbital plane. Maintaining TSS where the gravity is low represents another problem. There are also many problems involving multibody TSS of open-chain type and closed type in the presence of environmental forces including gravity perturbations, aerodynamic forces, free molecular reaction forces, solar radiation, and electromagnetic forces for conducting tethers. The multibody TSS in Earth–moon/Earth–sun Lagrangian points, as well as other planets such as Jupiter where the aerodynamic forces are predominant, pose challenging problems. For multitether systems, it is necessary to examine tether vibration issues. Apart from these issues, as has been experienced, the TSS in space has sometimes not performed as predicted and has resulted in failure of the missions. Work on the reliability of the control strategies, deployer, tether, and on the system as a whole should be more focused. With this wide body of work, it is hoped that the day will come when tether applications revolutionize space research and bring about the realization of the dream of low-cost access to space.

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