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Energy dissipation/transfer and stable attitude of spatial on-orbit tethered system

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ABSTRACT

For the Tethered Satellite System, the coupling between the platform system and the solar panel is a challenge in the dynamic analysis. In this paper, the coupling dynamic behaviors of the Tethered Satellite System that is idealized as a planar flexible damping beam-spring-mass composite system are investigated via a structure-preserving method. Considering the coupling between the plane motion of the system, the oscillation of the spring and the transverse vibration of the beam, the dynamic model of the composite system is established based on the Hamiltonian variational principle. A symplectic dimensionality reduction method is proposed to decouple the dynamic system into two subsystems approximately. Employing the complex structure-preserving approach presented in our previous work, numerical iterations are performed between the two subsystems with weak damping to study the energy dissipation/transfer in the composite system, the effect of the spring stiffness on the energy distribution and the effect of the particle mass on the stability of the composite system. The numerical results show that: the energy transfer approach is uniquely determined by the initial attitude angle, while the energy dissipation speed is mainly depending on the initial attitude angle and the spring stiffness besides the weak damping. In addition, the mass ratio between the platform system and the solar panel determines the stable state as well as the time needed to reach the stable state of the composite system. The numerical approach presented in this paper provides a new way to deal with the coupling dynamic system and the conclusions obtained give some useful advices on the overall design of the Tethered Satellite System.

1. Introduction

The report on the idea of the Solar Power Satellite System (SSPS) in 1968 [1] initiated a space solar energy developing era. Following this idea, several feasible structure concepts of SSPS were proposed, such as 1979 Solar Power Satellite (SPS) Reference System, Distributed Tethered Satellite System, Solar Sail Tower and SPS via Arbitrarily Large Phased Array. Among which, the structure expandability of the Distributed Tethered Satellite System concept has aroused considerable concern.

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Unfortunately, the early experiments in 1992 and 1996 on the Tethered Satellite System failed due to some structure dynamic problems, which promoted the dynamic analysis on the Tethered Satellite System in the past three decades. The representative works in this field include: Carroll [2], Guerriero and Vallerani [3] gave a general overview of the many ways that tethers might be used in space transportation or in space station operations, which inspired many researchers to investigate the dynamic behaviors of the spatial tether and exploit the applications of tethers in spatial structures; Dematteis and Desocio investigated the equations governing the motion of a subsatellite and its tether to show the influence of the aerodynamic forces on the equilibrium states of the system and the corresponding perturbed motion [4]; Keshmiri, Misra and Modi studied the dynamics of tethered N-body systems [5] and proposed various control strategies to stabilize the dynamics during retrieval of the subsatellite [6]; Forward, et al. investigated some fundamental problems of an electrodynamic drag Terminator Tether and indicated that electrodynamic drag can be used to remove a spacecraft from a typical 700–2000 km low Earth orbit constellation orbit within a few months using an ultra-light Terminator Tether system, but, unfortunately, the dynamic problems of the Terminator Tether system were ignored [7]; Leamy and his colleagues employed two finite element analysis codes to perform the dynamic simulations for the National Aeronautics and Space Administration (NASA) planned propulsive small expendable deployer system (ProSEDS) space tether mission and investigated the sensitivity of the codes in detail [8]; Mankala and Agrawal developed three models to perform the dynamic simulation of a tether [9]; Modeling the tether as a perfectly flexible, massive, continuous, visco-elastic string and modeling endbodies either as point masses or rigid bodies, Krupa et al. investigated the modeling method, the numerical simulation of dynamics and the control strategies for the tethered satellite systems [10]; Ishimura and Higuchi studied coupling phenomena between structural deformation and attitude motion of a planar space structure suspended by multi-tethers based on the finite element idea and found that the coupling occurred for low tether stiffness or a number of the tethers become slack [11], the model developed in which was finite dimensional and the structure damping of the planar was ignored; Cartmell, et al. reviewed the researches about the space tethers as well as their potential for propulsion of payloads in space [12], and investigated the dynamic behaviors of the spatial tethers system in detail [13–16], in which, only the orbit dynamic behaviors or the orbit-attitude dynamic behaviors of the tethered system were revealed for the limitation of the finite dimensional models established (such as the dumb-bell tether model); Pizarro-Chong and Misra examined the dynamics behaviors of certain multi-tethered satellite formations containing a parent body, in which, the satellites was assumed point-masses and the tethers was assumed straight [17]; Wen, Jin and Hu reviewed the historic background and recent hot topics associated with the dynamics and control of the space tethers [18]; Cai and her colleagues presented the nonlinear coupling dynamics of multi-tethered satellite system in a hub-spoke configuration without linearization and performed the numerical simulation on it [19,20], the limitation of the model established by Cai lies in that the tether just plays the geometric constraint role between the masses; Kruijff and van der Heide highlighted the design, qualification and mission performance of the tether deployer system on the second Young Engineers' Satellite and discussed the associated mission results [21]; Tang, et al. studied the dynamics of variable-length tethers with application to tethered satellite deployment based on the flexible multibody dynamics method [22]; Jung, Mazzoleni and Chung proposed a two-piece dumbbell model both for a tethered satellite system with a moving mass [23] and for a three-body tethered satellite system with deployment or retrieval [24]; The modeling method for the spatial flexible beam presented by Wu and his colleagues [25] gives some suggestions on the modeling process for the composite system considered in this paper; Yu, Jin and Wen studied the nonlinear dynamics of a flexible tethered satellite system subject to space environments [26].

Most of the above works on the dynamics of the tethered satellite system simplified the models in the following ways: modeling endbodies as point masses/rigid bodies and modeling the tethers as tensioned/loose strings. The limitation of modeling endbodies as point masses/rigid bodies is that both the structure damping and the structure deformation cannot be taken into account, which may result in certain error in the dynamic analysis of the ultra-large tethered satellite system. While the tethers are modeled as tensioned/loose strings, the energy transfer between the endbodies can only be considered at the tensioning moment of the tether. Thus, on the one hand, the damping, the elastic deformation and the vibration of some endbodies will be considered; on the other hand, the tethers will be modeled as springs to investigate the coupling effects between the tethers and the endbodies in this paper.

Considering the coupling between the planar motion and the transverse vibration, the dynamic behaviors of the planar flexible damping beam were investigated by a complex structure-preserving method in our previous work [27], the numerical results of which imply that both the coupling effects and the weak structure damping cannot be neglected in the long-term dynamic analysis of the spatial structure. In addition, the excellent long-term numerical behaviors of the structure-preserving approach that connects the classic fourth order Runge-Kutta method and the generalized multi-symplectic method [28–31] based on the multi-symplectic idea [32,33] were illustrated in our previous work [27].

Thus, in this continuing work, the dynamic model of a planar flexible damping composite system describing a simple tethered satellite system will be proposed and the coupling dynamic behaviors of which will be investigated by the structure-preserving approach in detail. This paper is organized as follows. In section 2, based on the variational principle, the dynamic model controlling the plane motion of the planar damping beam-spring-mass composite system and the transverse vibration of the planar flexible damping beam is deduced. In this model, the coupling effect between the plane motion of the system, the oscillation of the spring and the transverse vibration of the flexible damping beam are taken into account, which is the novelty of the dynamic model developed in this paper. And then, a symplectic dimensionality reduction method is proposed based on the symplectic manifold theory and the multi-symplectic manifold theory to decouple the dynamic model approximately, which is a structure-preserving dimensionality reduction indeed. For the almost decoupled system, the