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Gravitational orbit–attitude coupling dynamics of a large solar power satellite

Yuliang Liu[a,b], Shunan Wu[a,b,*], Kaiming Zhang[a,b], Zhigang Wu[a,b]

[a] *School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, PR China*
[b] *State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, PR China*

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ABSTRACT

The gravitational coupling of the orbit and attitude motions of a large flexible solar power satellite (SPS) is studied in this paper. The orbital and attitude dynamical equations of a SPS with flexible vibration are firstly derived. Then, the gravitational force and torque are expanded to the fourth order of a Taylor series in the small size/orbital ratio. The gravitational forces and torques generated by the Sun, the Moon and the oblateness of the Earth are also investigated. The simulation examples are finally presented, and the results have demonstrated that the higher order gravitational force and torque of the Earth have great influences on the orbital motion and ground pointing precision of the SPS.

1. Introduction

The solar power satellite (SPS) concept, firstly proposed by Peter Glaser in 1968 [1], consists of three main components: a solar array to collect solar radiation and convert it into direct current (DC) electricity, a DC-to-microwave converter and an antenna that directs a microwave beam towards the surface of the Earth. The main benefits of a SPS as opposed to a solar power system on the ground are that sunlight is not attenuated by the Earth's atmosphere, collection is not influenced by the day–night cycle and the SPS has higher end-to-end efficiency [2].

Currently, different SPS concepts have been proposed by NASA, JAXA, ESA, CAST and others [3,4]. A reference system which was defined that consisted of a large solar array (5.3 km × 10 km) was first designed by NASA. After that, the SPS Exploratory Research and Technology program studies, conducted by NASA in the 2000s, produced a variety of new configurations of SPS, such as Abacus, Cylindrical configuration, and so on [3]. There are also some configurations that were put forward by some European research institutes, such as Sun Tower solar power satellite (as shown in Fig. 1). And a new concept called multi-Rotary Joints SPS has been recently proposed by CAST researcher in China [4]. There are more than twenty kinds of configurations that were designed in the world so far. With the developments of the generating efficiency of solar panels and the technology of microwave transmission, the cost of a SPS will reduce to the level of business value. So it is necessary to study the problems of SPS faced by people.

Due to small size of traditional satellites, the orbits are assumed Keplerian and the spacecrafts' attitude motions are studied independently. The gravitational coupling of the orbit and attitude motions is often neglected. While for most satellites this is reasonable. The magnitude of this coupling is governed by size and mass distribution [5]. As the increase of spacecrafts' size, such as SPS, the gravitational coupling may be significant. In these cases, the coupling should be considered in theoretical studies and numerical simulations.

The effects of the gravitational coupling of SPS on the orbit and attitude motions have not been studied previously. The orbit and attitude motions are assumed to be uncoupled [6–12]. Graf first analyzed the characteristics of the orbital motion of a SPS [6]. Wie preliminarily studied the short-term orbital motion with external disturbances and designed a controller for orbit keeping. He also designed a PD controller for the attitude motion with the method of frequency band isolation [7,8]. Ian Mcally put forward an alternative solar power satellite orbital location, known as the geosynchronous Laplace plan (GLP), which is superior to geostationary in many aspects [9,10]. He also analyzed the attitude motion without control in the new orbit [11]. Shunan Wu designed a Sun-pointing control system for a SPS [12].

In terms of the studies about the gravitational orbit–attitude coupling of satellites, Duboshin first derived the differential equations of the orbit and attitude motions of two bodies with arbitrary shapes [13]. Lange and Mohan studied the orbit–attitude coupling of a conventional spacecraft which moves in the Earth's central

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[*] Corresponding author at: School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, PR China. Fax: +86 411 84706202.
E-mail address: wushunan@dlut.edu.cn (S. Wu).

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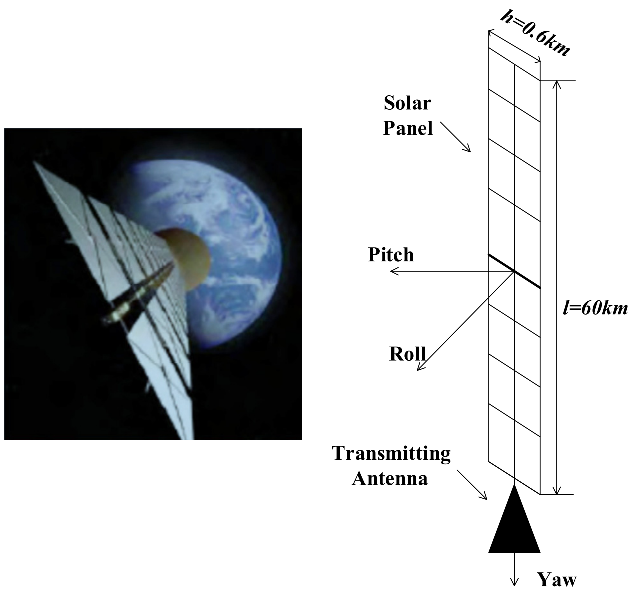

Fig. 1. The configuration of the Sun Tower SPS.

field. The interdependence of the orbit and attitude motions is shown explicitly by expanding the differential gravitational force and torque in a Taylor series in the small parameter $\varepsilon = \rho/R$, where ρ is the characteristic of spacecraft size and R is the orbital radius [14,15]. Lange and Mohan neglected the terms which are higher than ε^2. In order to estimate the effects of higher terms of ε on an extremely large structure, Hughes studied a large board-like satellite, which only neglected the terms of higher than ε^4 [5]. Ashenberg investigated the mutual gravitational potential of two bodies with arbitrary shapes which are expended to the fourth order via inertia integrals [16]. By using the method which Ashenberg put forward, Yue Wang analyzed the orbit–attitude coupling of a spacecraft with a particular shape around a spheroid plant [17]. Recently, the coupled orbit–attitude dynamics of spacecraft in various dynamical environments has drawn much attention. Gaurav investigated the coupled orbit–attitude dynamics of a spacecraft near a small solar system bodies, which the gravitational potential was expended up to the second degree and the influence of solar radiation pressure was considered [18]. Wang studied the stability of relative equilibria for the full dynamics of a spacecraft around an asteroid, in which the spacecraft is assumed to be a rigid body and the gravitational orbit–attitude coupling is taken into account [19]. He also addressed the orbital dynamics and equilibrium points of a spacecraft around an asteroid with gravitational orbit–attitude coupling perturbation [20]. Wang proposed a Hamiltonian structure-based feedback control law to stabilize the coupled orbit–attitude dynamics of a rigid body in J_2 gravity field [21]. The orbit–attitude behaviors of rigid bodies in the circular restricted three-body problem were studied by Guzzetti [22,23]. Amanda investigated the attitude responses of a rigid spacecraft in coupled orbit–attitude dynamical model in Earth–Moon Lyapunov orbits [24].

In this article, the orbit–attitude coupling of a Sun Tower SPS is studied. The paper is organized as follows. In section 2, the orbital and attitude dynamical equations of a SPS with flexible vibration are derived. In section 3, the gravitational potential of a SPS up to fourth order of ε is established and then the gravitational forces and torques generated by the Earth, the Sun and the Moon are derived. The equations of motions which are used for numerical simulation are given in section 4. Numerical simulation examples are then presented in section 5. Finally, the paper is concluded in section 6.

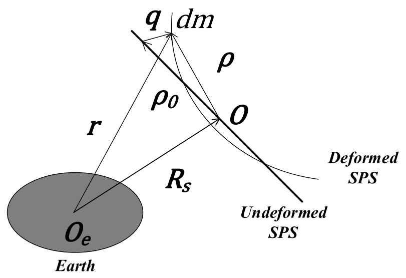

Fig. 2. The Sun Tower SPS in the Earth's orbit.

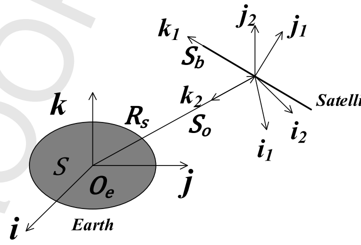

Fig. 3. The schematic diagram of different reference frames.

2. The influence of flexible vibration on orbit and attitude motions

In this section, the orbital and attitude dynamical equations of a Sun Tower SPS with flexible vibration are derived. A Sun Tower SPS moves in the gravitation field of the Earth. As $h \ll l$, where $l = 60$ km is the length of the SPS; $h = 0.6$ km is the width of the SPS, as shown in Fig. 1. The SPS is simplified as a flexible beam with boundary of free–free.

As shown in Fig. 2, the position vector which is from the Geocentric to the SPS mass-center is denoted by $\boldsymbol{R_s}$, where O_e and O denote the Geocentric and the mass-center of SPS, respectively. $\boldsymbol{\rho}$ denotes the position vector which is from O to the unit mass dm for the deformed SPS; $\boldsymbol{r}$ denotes the position vector which is from O_e to the unit mass dm with $\boldsymbol{r} = \boldsymbol{R_s} + \boldsymbol{\rho}$; $\boldsymbol{\rho_0}$ denotes the position vector which is from O to the unit mass dm for the SPS of undeformation; $\boldsymbol{q}$ denotes the vector of the deformations with $\boldsymbol{\rho} = \boldsymbol{\rho_0} + \boldsymbol{q}$.

The deformations are assumed to be small and described as [25]:

$$\boldsymbol{q} = \sum_{n=1}^{\infty} A_n(t)\boldsymbol{\varphi}^{(n)}(\boldsymbol{\rho_0}) \tag{1}$$

where $\boldsymbol{\varphi}^{(n)}(\boldsymbol{\rho_0}) = \varphi_x^n \boldsymbol{i_1} + \varphi_y^n \boldsymbol{j_1} + \varphi_z^n \boldsymbol{k_1}$ is the n-th order mode shape of free vibration, which is associated with a modal amplitude $A_n(t)$; $\boldsymbol{i_1}, \boldsymbol{j_1}, \boldsymbol{k_1}$ are the unit vectors of the body-fixed reference frame of the SPS with $S_b = (\boldsymbol{i_1}, \boldsymbol{j_1}, \boldsymbol{k_1})$, as shown in Fig. 3. The frame S_b coincides with the principal axes reference frame of the SPS. The mode shape satisfies the following conditions of orthogonality to the other modes [25]:

$$\int \boldsymbol{\varphi}^{(n)}(\boldsymbol{\rho_0}) dm = 0 \tag{2a}$$

$$\int \boldsymbol{\rho_0} \times \boldsymbol{\varphi}^{(n)}(\boldsymbol{\rho_0}) dm = 0 \tag{2b}$$

$$\int \boldsymbol{\varphi}^{(n)}(\boldsymbol{\rho_0}) \cdot \boldsymbol{\varphi}^{(m)}(\boldsymbol{\rho_0}) dm = \delta_{nm} M_n \tag{2c}$$

where δ_{nm} is the Kronecker delta, M_n is the generalized mass of n-th mode.

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