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# Coupling dynamics of super large space structures in the presence of environmental disturbances

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ABSTRACT

Considering the effects of the gravity gradient, the solar radiation pressure (SRP) and the thermal radiation, the coupling dynamical model is established for a super large flexible beam structure, which moves in the orbital plane around the earth. The effects of environmental disturbances on the orbital motion, the attitude motion and the structural vibration are analyzed simultaneously. Influences of the initial attitude angle, the structure size and other system parameters have been investigated for the coupling dynamics. The results show that the envelop shapes of the vibration responses are dependent on the attitude motion, and the perturbation of orbital motion increases with the growth of the initial attitude angle. When the structural fundamental frequency is close to the attitude frequency with the increase of the structure size, the average orbit altitude would decrease slightly. The main frequency component of the attitude motion decreases and the frequency component related to the structural vibration encounters and grows up. The resonance then leads to system instability. Moreover, the magnitude of the attitude motion can also be influenced by the slightly intense structural vibration, which might be excited by the momentum exchange devices of the attitude control system. In addition, in the presence of the SRP, the orbital radius is perturbed obviously and the eccentricity of orbital motion is generally changed. The effects of the thermal radiation and the gravity gradient are in the same order of magnitude on the structural vibration in the low orbit while the former one turns to be dominant in geostationary orbit.

## 1. Introduction

The solar power satellite (SPS) concept was proposed by Peter Glaser in 1968 [1]. It is a promising methodology to provide earth with primary power. Since the invention of SPS concept, there are numerous research activities and various SPS concepts have been proposed by NASA [2], JAXA [3], ESA [4], CAST [5] and others institutes [6]. Due to the mission of solar power collection and the micro gravitational environment, the sizes of all the SPS configurations reach up to several kilometers. The super large scale and flexibility thus become the most special characteristic of the SPS. These structural features arouse the sophisticated phenomena and problems about the coupling among the orbital motion, attitude motion and vibration. The accurate prediction of the orbital motion, attitude motion and vibration is therefore quite essential, not only for the on-orbit assembly, but also for operation during the long terms. Thus, the research on the coupling dynamics of such super large space structures in the presence of the environmental disturbances are the essential and indispensable.

There are few investigations for the coupling dynamics of super large space structures. Some researchers studied the coupled orbital and attitude motion of the rigid large space structures. Wie [7] discussed the effects of several environmental disturbance on the orbital and attitude motion based on the Abacus configuration which is mainly a plate structure. Sincarsin [8] also investigated the motion for a plate-like spacecraft and the orbit-attitude coupled phenomenon was discovered. He introduced a practical recursive definition for higher moments of inertia, which is very useful in the presence of gravity gradient. Meanwhile, the gravitational coupling was studied by Liu [9] the for the orbit and attitude motions based on a one-dimension SPS configuration and found that the higher order gravitational force and torque have appreciate influences on motions.

Although Wie pointed out that the frequency of the structural fundamental vibration is much lower than that of attitude motion and the vibration may not be a major concern for attitude control, some couple phenomena were found based on the classical models, such as the dumbbell, the beam and others. Malla [10] and Ishimura [11] both focused attentions on the space dumbbell. The effects of orbital, attitude and structural initial conditions and the system parameters

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including ratios of mass, frequency and length was discussed on the coupling motion. It was observed that the structure's axial and attitude motions were appreciably affected by the initial values of the axial deformation and pitch angle and the natural frequency ratio, whereas these parameters had negligible effects on the structure's orbital motion. The effects of flexibility on the inertial terms and the that of the attitude control on the elastic parameters was discussed with a simplified satellite FEM model by Gasbarri [12]. Beyond the Earth's orbit, Colagrossi [13] investigated the coupling motions in Halo orbits and the effects due to the large structure flexibility were emphasized.

Meanwhile, the stability and the resonance were also concerned. Sanyal [14,15] analyzed the controllability and stability of the system based on the linear perturbation equation of the space dumbbell. He stressed the effect of large-scale size on the eigenvalue of the motions. Among several classical structural configurations, Ashley [16] primarily compared the influence of the gravity gradient, where only the first order of the gravity gradient was retained. And some buckling instability of the elastic deformation in the dumbbell and the rod was discussed. Silva [17,18] used the perturbation methods to analyze several resonant motions of the beam structure exhibited by the system, which are associated with very low excitation frequencies. Considering the effects of dynamic stiffening, Liu [19] proposed a parametrical excitation model (PEM) to describe the beam vibration and more accurate structural vibration could be obtained using this model.

As for the super large space structure, the effects of the thermal radiation and the SRP could not be negligible any more due to its large ratio of area to mass. Malla [20] studied the thermal radiation effects on the structural deformation and attitude libration for the space dumbbell in a planar pitch motion. Ishimura [21] discussed a planar structure suspended by multi-tethers with the thermal deformation, which was found to be one cause of tether slack and makes roll and yaw motions unstable. Krishna [22] investigated the effect of the SRP for the thermally deformed beam structure and found it to disturbance moments for the deformation of the structure.

In this study, the coupling equations governing a planar pitch motion around the Earth of a super large flexible beam-like structure are formulated. The environmental disturbances, including the gravity gradient, the SRP and the thermal radiation, are all taken into consideration. In Sec. 2, the coupling dynamical model is presented. The method to determine the Earth's shadow and the thermal analysis are introduced in Sec. 3. In the last Section, the numerical results are discussed focusing on the coupling phenomenon and the effects of the SRP and thermal radiation.

## 2. Equations of motion

The geometric configuration under consideration consists of a very slim and flexible beam representing a super large space structure. The beam moves in a general noncircular orbit around the spherical Earth of radius $R_e$ with center at $O_e$ (Fig. 1). This beam structure is assumed to move in the orbital plane (coplanar motion). It is also assumed that the orbit of the structure is defined by the motion of its center of mass (CM).

The inertial frame and the orbital frame are both centered at the point $O_e$, which are represented as $O_e x_e y_e$ and $O_e x_o y_o$ respectively. The floating reference frame centered at CM, represented as $Cxy$, rotates with the beam structure. The coordinate vector and deformation vector of the arbitrary point $P$ of the beam are represented as $\boldsymbol{\rho}_P$ and $\mathbf{w}_P$. The point $A$ is located at the tip of the beam, and its displacement is chosen on behalf of the response of the structural vibration. Due to the definition of the floating reference frame, these two vectors satisfy the following conditions of centroid constraint, linear and angular momentum conservation:

$$\int_V \rho(\boldsymbol{\rho}_P + \mathbf{w}_P)\mathrm{d}V = \int_V \rho\boldsymbol{\rho}_P\mathrm{d}V = \int_V \rho\mathbf{w}_P\mathrm{d}V = 0 \tag{1}$$

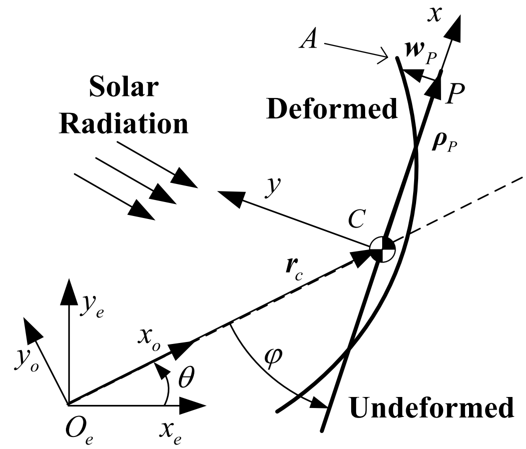


**Fig. 1.** Large orbiting structure in space environment.

$$\int_V \rho\dot{\mathbf{w}}_P\mathrm{d}V = 0 \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)^{\mathrm{T}}\dot{\mathbf{w}}_P\mathrm{d}V = 0 \tag{3}$$

where $(\dot{*})$ and $(\tilde{*})$ represent the derivation of time and the cross antisymmetric matrix of the original vector, and $V$ represents the whole volume of the space structure. The radius vector $\mathbf{r}_p$ of the point $P$ is expressed as

$$\mathbf{r}_p = \mathbf{T}_{eo}\mathbf{r}_c + \mathbf{T}_{eo}\mathbf{T}_{oa}(\boldsymbol{\rho}_P + \mathbf{w}_P) \tag{4}$$

where $\mathbf{T}_{eo}$ is coordinate transformation matrix from orbital frame to inertial frame, while $\mathbf{T}_{oa}$ is one from floating reference frame to orbital frame.

The kinetic energy of the beam is given by

$$\begin{aligned} T &= \tfrac{1}{2}\int_V \rho\|\dot{\mathbf{r}}_{p,a}\|^2\mathrm{d}V \\ &= \tfrac{1}{2}\int_V \rho[\|(\dot{\mathbf{r}}_c + \tilde{\boldsymbol{\omega}}_{eo}\mathbf{r}_c)\|^2 + 2(\dot{\mathbf{r}}_c + \tilde{\boldsymbol{\omega}}_{eo}\mathbf{r})^{\mathrm{T}}\mathbf{T}_{oa}\dot{\mathbf{w}}_P \\ &+ 2(\dot{\mathbf{r}}_c + \tilde{\boldsymbol{\omega}}_{eo}\mathbf{r}_c)^{\mathrm{T}}\mathbf{T}_{oa}(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)(\mathbf{T}_{oa}{}^{\mathrm{T}}\boldsymbol{\omega}_{eo} + \boldsymbol{\omega}_{oa}) + \|\dot{\mathbf{w}}_P\|^2 \\ &+ 2(\mathbf{T}_{oa}{}^{\mathrm{T}}\boldsymbol{\omega}_{eo} + \boldsymbol{\omega}_{oa})^{\mathrm{T}}(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)^{\mathrm{T}}\dot{\mathbf{w}}_P + (\mathbf{T}_{oa}{}^{\mathrm{T}}\boldsymbol{\omega}_{eo} + \boldsymbol{\omega}_{oa})^{\mathrm{T}} \\ &\cdot(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)^{\mathrm{T}}(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)(\mathbf{T}_{oa}{}^{\mathrm{T}}\boldsymbol{\omega}_{eo} + \boldsymbol{\omega}_{oa})]\mathrm{d}V \end{aligned} \tag{5}$$

where $\dot{\mathbf{r}}_{p,a}$ is the velocity vector in the floating reference frame and the identifier $\|*\|$ represents the two norm of a vector. $\boldsymbol{\omega}_{eo}$ and $\boldsymbol{\omega}_{oa}$ are angular velocity vectors of the orbital frame and the floating reference frame. Due to conditions (1)–(3), the kinetic energy is simplified as

$$\begin{aligned} T &= \frac{m_s}{2}\|\dot{\mathbf{r}}_c + \tilde{\boldsymbol{\omega}}_{eo}\mathbf{r}_c\|^2 + \frac{1}{2}\int_V \rho\|\dot{\mathbf{w}}_P\|^2\mathrm{d}V \\ &+ \frac{1}{2}(\mathbf{T}_{oa}{}^{\mathrm{T}}\boldsymbol{\omega}_{eo} + \boldsymbol{\omega}_{eo})^{\mathrm{T}}\mathbf{I}(\mathbf{T}_{oa}{}^{\mathrm{T}}\boldsymbol{\omega}_{eo} + \boldsymbol{\omega}_{eo}) \end{aligned} \tag{6}$$

where $m_s$ represents the total mass of the structure, and $\mathbf{I}$ represents the moment of inertia of the structure and is given by

$$\mathbf{I} = \int_V \rho(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)^{\mathrm{T}}(\tilde{\boldsymbol{\rho}}_P + \tilde{\mathbf{w}}_P)\mathrm{d}V$$

The gravitational potential energy of the beam is

$$V_G = -\int_V \frac{\rho\mu}{\|\mathbf{r}_p\|}\mathrm{d}V \tag{7}$$

The denominator of the gravitational potential energy can be expanded in a Taylor series in the small ratio (spacecraft size/orbital radius).