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Deployment and retrieval of a rotating triangular tethered satellite formation near libration points

Zhiqin Cai *, Xuefu Li, Zhigang Wu

Department of Engineering Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, 2 Linggong Road, Ganjingzi District, Dalian 116024, Liaoning, PR China

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ABSTRACT

The dynamic stability of a rotating triangular tethered satellite formation near libration points during the deployment and retrieval stages is investigated. Based on Hill's approximation, a new dynamical formulation for the attitude and orbital motions of the system is developed. Using numerical simulations, parametric studies of the effects of the orbital amplitude, initial rotation rate, tether length, and length rate are performed. It is shown that different initial rotation rates or length rates have almost no impact on the trajectories of the system's centroid. As expected, increasing the initial rotation rate or reducing the length rate can improve the stability of a tethered satellite system.

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1. Introduction

The circularly restricted three-body problem (CRTBP) has five libration points, called the equilibrium or Lagrangian points. Three of these points are situated on a line joining the two attracting bodies, and the other two points form equilateral triangles with these bodies. For the Sun–Earth system, the L_2 point lies beyond the Earth on the line defined by the Sun and Earth. It will be an ideal location for a number of large astronomical observatories over the next two decades [1]. Satellite formation systems can be utilised for a variety of space missions and different types of planetary science. Tethers have been used in National Aeronautics and Space Administration (NASA) space missions, SEDS-1, SEDS-2, TSS-1, and TSS-1R, for the deployment of satellites [2–5]. More missions for the tethered satellite system have been performed in recent years, such as the TiPS, ATEx, and YES 2 [6–8].

Tethered satellite formation flying has advantages over traditional single satellites. Such advantages include fewer station maintenance costs, superior reliability to maintain the formation's geometry, and better adaptability for wider applications. The reconfiguration of the tethers plays an important role in the process of achieving the objective formation and changing the flying speed. Numerous theoretical and experimental studies on the dynamics of tethered formations have been performed in recent years. Tragesser [9] derived the equations of motion for a ring formation with an arbitrary number of satellites and simulated three satellites to assess the stability of the system. Pernicka et al. [10] investigated the dynamics of a short, inextensible, tethered satellite in low Earth orbit. Pizarro-Chong et al. [11] investigated a hub-and-spoke multi-tethered formation and found that a spinning formation is stable for up to four bodies. Kumar et al. [12] analysed the rotating formation flying of three satellites that were connected with flexible, essentially massless tethers. The effects of the various parameters of the system and tether deployment/retrieval on the system response have also been investigated. Kim et al. [13] established the

* Corresponding author. Tel.: +86 13322279951.
E-mail address: zhqcai@dlut.edu.cn (Z. Cai).

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equation of motion for a tethered satellite system and estimated the total required control impulse for a NASA mission. Lee et al. [14] utilised geometric numerical integration to develop a high-fidelity analytical model and numerical simulations for tethered spacecraft. Agrawal et al. [15] developed the dynamic equations of motion for a tether system rotating around Earth using Hamilton's principle. Williams [16] established a dynamic model for a flexible tethered formation in an Earth orbit in which the closed triangular formations were simulated using a lumped parameter representation of the system. Several ground experiment systems and control methods have also been designed [17–21]. Almost all of these studies have assumed that the attitude and orbital motions were independent, and few papers have combined these aspects. However, the orbital motion near the L_2 point is inherently unstable, and very small perturbations can lead to a failure to maintain the formation and a departure from the object's orbit. Hence, a coupled model is required to study the dynamics of formation deployment and retrieval near libration points.

Several studies have addressed tethered satellite formations near libration points. Gates [22] established motion and tether tension equations for an arbitrarily configured multi-tethered system near libration points in the CRTBP. Zhao and Cai [23] investigated nonlinear coupled dynamics of multi-tethered satellite formations in which the parent satellite follows three-dimensional large Halo orbits centred about the L_2 point of the Sun–Earth system. However, there has been little research on the reconfiguration dynamics for triangular tethered satellite formation. A triangular tethered satellite formation can easily maintain stability by rotating, allowing it to reduce the cost of station keeping.

In this paper, a dynamic model for a rotating triangular tethered satellite formation near the libration points is established in Section 2. This model is based on Hill's restricted three-body problem (HRTBP) and couples the attitude and orbital motions. Numerical simulations are then performed to study the stabilities of the formation in the deployment and retrieval stages. The influences of the reconfiguration parameters are also studied. The stability of the orbital motion is analysed in Section 3 and the attitude of the formation is simulated in Section 4. Finally, some conclusions are drawn in Section 5.

2. Dynamic model

2.1. Description of the system

In this paper, we derive the dynamic model of the rotating triangular tethered satellite formation near the L_2 libration point based on HRTBP, which is a simplified version of the CRTBP. Compared with the CRTBP, HRTBP has the advantage of a simple set of equations with no parameters and includes symmetries that simplify the numerical computations [24,25]. By utilising the Hill approximation, the relative error is on the order of 1.5% for the Sun–Earth system [26]. The closed-loop rotating triangular tether formation model considered in this paper is illustrated in Fig. 1. The system is modelled as a set of point masses that are connected via inextensible, massless tethers that are always tight. The masses of the satellites are denoted by m_1, m_2, and m_3. The tethers are denoted by l_1, l_2, and l_3.

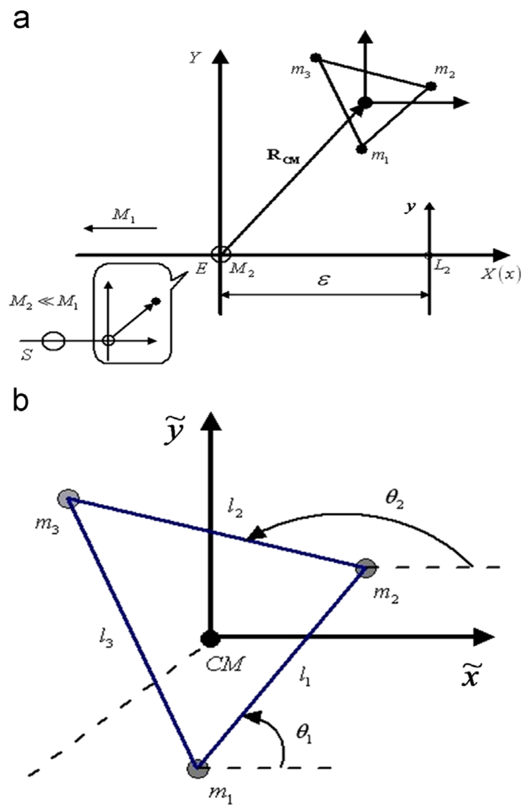

Fig. 1. The system model: (a) the global model and (b) the local coordinate system S_{CM}.

In HRTBP, the motion of the system is described using a set of body-centred rotating coordinates, E-XYZ (denoted by S_E), with the origin at Earth. The X-axis points positively outward from the Sun to Earth, the Y-axis is perpendicular to the X-axis in the plane of motion of the primary bodies, and the Z-axis is normal to the X–Y plane. The orbits centred at L_2 are described using an additional set of coordinates, L_2-xyz (denoted by S_L), with the origin at the second libration point and otherwise parallel to S_E. A local coordinate system, $S_{CM}-\tilde{x}\tilde{y}\tilde{z}$ (denoted by S_{CM}), is established to describe the tethered end masses, with the origin at the system's centre of mass (CM) and parallel to the x, y, and z axes. The in-plane rotation angles, $\theta_i\,(i=1,2)$, are measured counter clockwise from the positive $\tilde{x}$ axes to the $\tilde{z}$ axes.

2.2. Derivation of the equations of motion

The position vector of the CM relative to Earth in S_E is denoted by $\boldsymbol{R_{CM}}$. The position of the ith satellite in coordinate S_{CM} is denoted by $\mathbf{r}_i$. The CM constraint is represented by

$$\sum_{i=1}^{3} m_i \cdot \mathbf{r}_i = 0 \tag{1}$$

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