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Stability of relative equilibria of the full spacecraft dynamics around an asteroid with orbit–attitude coupling

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Abstract

The full dynamics of spacecraft around an asteroid, in which the spacecraft is considered as a rigid body and the gravitational orbit–attitude coupling is taken into account, is of great value and interest in the precise theories of the motion. The spectral stability of the classical relative equilibria of the full spacecraft dynamics around an asteroid is studied with the method of geometric mechanics. The stability conditions are given explicitly based on the characteristic equation of the linear system matrix. It is found that the linearized system decouples into two entirely independent subsystems, which correspond to the motions within and outside the equatorial plane of the asteroid respectively. The system parameters are divided into three groups that describe the traditional stationary orbit stability, the significance of the orbit–attitude coupling and the mass distribution of the spacecraft respectively. The spectral stability of the relative equilibria is investigated numerically with respect to the three groups of system parameters. The relations between the full spacecraft dynamics and the traditional spacecraft dynamics, as well as the effect of the orbit–attitude coupling, are assessed. We find that when the orbit–attitude coupling is strong, the mass distribution of the spacecraft dominates the stability of the relative equilibria; whereas when the orbit–attitude coupling is weak, both the mass distribution and the traditional stationary orbit stability have significant effects on the stability. We also give a criterion to determine whether the orbit–attitude coupling needs to be considered.

Keywords: Second degree and order-gravity field; Full spacecraft dynamics; Gravitational orbit–attitude coupling; Relative equilibria; Spectral stability; Non-canonical Hamiltonian structure

1. Introduction

The knowledge of the physical and dynamical properties, distribution, formation, and evolution of the small bodies, i.e., asteroids and comets, is fundamental to understand the solar system origin and early evolution, possibly including the development of life on Earth (Barucci et al., 2011). Space missions have played an important role in our understanding of small bodies. Several missions have been developed with big successes, such as NASA's Near Earth Asteroid Rendezvous (NEAR) to the asteroid Eros and JAXA's mission Hayabusa to the asteroid Itokawa. Moreover, near-Earth objects (NEOs) represent a threat to our planet (Sanchez et al., 2009). On average, every 26–30 million years a 10-km-sized asteroid strikes Earth, and every several hundred years there is a Tunguska-class (100 m in diameter) asteroid impact (Stokes and Yeomans, 2003). The space community has turned its attention to the impact risk NEOs pose to our fragile ecosystem. The growing interest in these small bodies has translated into an increasing number of small body missions. All the major space agencies are involved on missions to asteroids for scientific exploration or NEO hazard mitigation, such as the asteroid sample return missions OSIRIS-REx (Lauretta et al., 2012), MarcoPolo-R (Michel et al., 2014) and Hayabusa 2 (Tsuda et al., 2013), and asteroid deflection

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missions DART (Cheng et al., 2012), AIDA (Galvez et al., 2013) and NEOShield (Harris et al., 2013).

A thorough understanding of the dynamical behavior of spacecraft near asteroids is necessary prior to the mission design. Since an asteroid is much smaller than Earth, the orbital radius can be very small when the spacecraft is in the proximity of an asteroid. Therefore, compared with the traditional spacecraft dynamics around Earth, the spacecraft dynamics around asteroids has a remarkable characteristic that the gravitational coupling between the orbital and rotational motions can be significant due to the large ratio of the dimension of the spacecraft to the orbit radius, as shown by Koon et al. (2004), Scheeres (2006b), Wang and Xu (2014). The magnitude of the gravitational orbit–attitude coupling can be described by the parameter $\varepsilon = \rho/r_0$, where ρ is characteristic dimension of the spacecraft and r_0 is the orbital radius (Sincarsin and Hughes, 1983). Due to the large dimension of Earth, the parameter ε is order of 10^{-6} for a spacecraft ($\rho \sim 10$ m) around Earth. However, ε can be order of 10^{-2} for a spacecraft on a 1 km orbit around a small asteroid with a 500 m radius.

In the traditional spacecraft dynamics, the orbital and attitude motions are treated as independent problems. The spacecraft is treated as a point mass in the orbital dynamics and consequently the orbit is not affected by the attitude motion. The attitude motion, treated as a restricted problem, is studied on a predetermined orbit (Maciejewski, 1997). The traditional spacecraft dynamics is precise enough for the spacecraft around Earth, since the orbit–attitude coupling is insignificant. However, it will no longer have a very high precision in the proximity of the small asteroids due to the significant orbit–attitude coupling.

The dynamics of spacecraft near asteroids have been studied broadly by many scholars, including both the orbital and attitude dynamics. There have been many works on the orbital dynamics of the spacecraft near an asteroid, such as Scheeres (1994, 2012a,b), Scheeres et al. (1996, 1998, 2000), Scheeres and Hu (2001), Hu (2002), San-Juan et al. (2002), Hu and Scheeres (2004), Hirabayashi et al. (2010), Liu et al. (2011a,b), Yu and Baoyin (2012a,b, 2013), Jiang et al. (2014) and Li et al. (2013). There also have been many works on the attitude dynamics of the spacecraft near an asteroid, such as Riverin and Misra (2002), Misra and Panchenko (2006), Kumar (2008), and Wang and Xu (2012a, 2013a,b,c,d). These previous works are all within the framework of the traditional spacecraft dynamics with the orbit–attitude coupling neglected. In the present paper, we will study dynamical behaviors of the spacecraft near an asteroid within a new framework, i.e., the full spacecraft dynamics.

The spacecraft is treated as a rigid body in the full spacecraft dynamics, and the coupled orbital and rotational motions are modeled within a unified approach with the gravitational orbit–attitude coupling considered. The full dynamics is more precise than the previous works on the dynamics near asteroids within the framework of the traditional spacecraft dynamics. Through studies on the full dynamics, we can provide more detailed properties of the dynamical behaviors around asteroids. These results will be very useful for the design of future technologies for the control and navigation of spacecraft near asteroids, which should be more precise than current technologies developed based on the traditional spacecraft dynamics.

The full spacecraft dynamics around an asteroid can be considered as a restricted model of the Full Two Body Problem (F2BP), i.e., two rigid bodies orbiting each other interacting through mutual gravitational potential. That is to say, in our problem we only study the motion of the spacecraft, and assume that the motion of the asteroid is not affected by the spacecraft. The sphere-restricted model of F2BP, in which one body is assumed to be a homogeneous sphere, has been studied broadly. The gravity field of the non-spherical body is truncated on the second-order terms (Kinoshita, 1970, 1972a,b; Barkin, 1979; Balsas et al., 2008, 2009). The non-spherical body has also been assumed to be a general rigid body (Aboelnaga and Barkin, 1979; Barkin, 1980, 1985; Beletskii and Ponomareva, 1990; Koon et al., 2004; Scheeres, 2006a), an ellipsoid (Scheeres, 2004; Bellerose and Scheeres, 2008a,b), a symmetrical body (Vereshchagin et al., 2010), a dumb-bell (Goździewski and Maciejewski, 1999), or a model of two material segments and a central mass (Breiter et al., 2005). There are also several works on the more general models of F2BP, in which both bodies are non-spherical, such as Maciejewski (1995), Mondéjar and Vigueras (1999), Scheeres (2002, 2009), Koon et al. (2004), Fahnestock and Scheeres (2006, 2008), Boué and Laskar (2009), McMahon and Scheeres (2013), and Woo et al. (2013). In Scheeres (2009), McMahon and Scheeres (2013), and Woo et al. (2013), the planar motion of F2BP has been studied, but the full motion in the three-dimensional space of F2BP has not been investigated.

The full dynamics of a rigid body in a central gravity field with gravitational orbit–attitude coupling has been investigated in several works (Wang et al., 1991, 1992; Teixidó Román, 2010). The relative equilibria and their stability of the full dynamics of a rigid body in a J_2 gravity field have been studied in Wang and Xu (2013e,f) and Wang et al. (2013). However, these results are only applicable to a spheroid central body, but not applicable to most of the general asteroids, the ellipticity coefficient C_{22} of which is also significant. Therefore, the studies of the full dynamics of a rigid body in a C_{20}–C_{22} gravity field are necessary for a spacecraft moving near an asteroid.

The majority of asteroids are nearly in a uniform rotation about their maximum-moment principal axis due to the nonlinear stability of this rotational state in presence of energy dissipation. In this paper, the full dynamics of a rigid spacecraft around a uniformly rotating asteroid is studied. The harmonic coefficients C_{20} and C_{22} of the gravity field of the asteroid are considered.

The relative equilibria and their spectral stability of the spacecraft are studied with the method of geometric