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Asteroid rotation control via a tethered solar sail

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Abstract

The rotation of asteroids causes difficulties in the exploration of asteroids or prevention of asteroids impact on the Earth. We propose to use a solar sail to control, i.e., slow down or stop the rotational motion of an asteroid. First, the dynamic model of a tethered solar sail in the rotating gravitational field of an asteroid is presented. An optimal control method is employed to determine the control law of the tethered solar sail. The optimal control problem is converted into a nonlinear programming problem with the Gauss pseudospectral method. Simulation results show that this method can effectively slow down or even stop the rotation of an asteroid. A solar sail of 10^5 m^2 can stop the rotation of the asteroid Apophis in 1000 days.

Keywords: Solar sail; Asteroid rotation; Tethered system; Optimal control; Gauss pseudospectral method

1. Introduction

Several methods have been proposed to prevent an asteroid impact on the Earth, such as: kinetic impact (Tate, 2003; McFadden et al., 2005; Dachwald et al., 2006; Stickle et al., 2015), nuclear explosion (Ahrens and Harris, 1992; Kaplinger et al., 2009; Wie, 2011; Pitz et al., 2012, 2014), gravity tractor (Edward and Stanley, 2005; McInnes, 2007; Wie, 2008; Olympio, 2010), mass driver (Brian, 1977; Friedman et al., 2004; Corbin and Higgins, 2006), Yarkovsky effect (Erik, 2002; Spitale, 2002; Sasi and Visakh, 2010; Hyland et al., 2014), laser ablation (Maddock et al., 2007; Gibbings et al., 2012; Vasile and Maddock, 2012) and tether-assisted methods (French and Mazzoleni, 2009, 2010; Mashayekhi and Misra, 2014). However, the effectiveness of most methods is affected by the asteroid rotation, which usually leads to unsuccessful missions. The rotation of an asteroid causes the ineffectiveness of kinetic impact and standoff nuclear explosion because channeling the force through the mass center of an asteroid is difficult. When laser ablation method is employed, the laser cannot be focused on a fixed area on the surface of an asteroid because of the rotation of the asteroid. Rotation can also cause the tether twining problem for the tether-assisted method. Therefore, we proposed to slow down or stop the rotation of an asteroid using a tethered solar sail.

Rotation is a basic characteristic of an asteroid. Significant effort has been focused on measuring and analyzing the spin state of asteroids (Binzel et al., 1989; Scheeres et al., 2000; Vasilkova, 2003; Wiegert, 2015). The rotation of an asteroid is influenced by impact, torques caused by multi-body gravitation, solar radiation pressure, Yarkovsky effect and precession. Viswanathan and Vaikuntanathan (2009) proposed to use a high-power Helmholtz coil magnetic field generator to change the spin rate of the asteroid to alter the Yarkovsky effect acting on it. The interior chemical composition of the asteroid should be electrically conductive when this approach is applied. This method also

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requires a clear understanding of the internal structure of the asteroid. Sanchez et al. (2009) and Vasile et al. (2014) noted that the ablation process will generate a higher thrust to an asteroid with low angular velocity than an asteroid with high angular velocity. Vetrisano et al. (2016) designed an on-board state estimation and control algorithm that can control the rotation of the asteroid and the relative motion between spacecraft and asteroid simultaneously. A variation of the spacecraft's motion produces a change in the modulus and direction of the deflection action which modifies the rotational motion of the asteroid. However a highly precise guidance, navigation and control system is needed to focus the laser.

Gao and Wu (2015) presented a method of changing the orbit of an asteroid with a tethered solar sail. This approach can make the asteroid deviate from its original orbit without damaging the asteroid. However, asteroid rotation was not considered. In the present study, we develop the function of the tethered solar sail. An optimal control method is used to control the tethered system to slow down the rotation of an asteroid. Without changing the length of the tether, the solar sail can be kept synchronous with the asteroid by using solar radiation pressure. The tether twining problem caused by the rotational motion of the asteroid can be avoided. By controlling the solar sail, the tether can be tightened. The force acting on the tether will continually produce a torque opposite to the rotation direction of the asteroid. The rotation rate of the asteroid can decrease.

First, the dynamic model of the solar sail in the rotating gravitational field of an asteroid is established. Then the optimal control problem of the tethered system is discussed by taking advantage of the Gauss pseudospectral method (Benson, 2005; Jorris and Mccracken, 2011; Bittner et al., 2012). Afterward, two scenarios are established for comparison. Finally, the simulation results are analyzed.

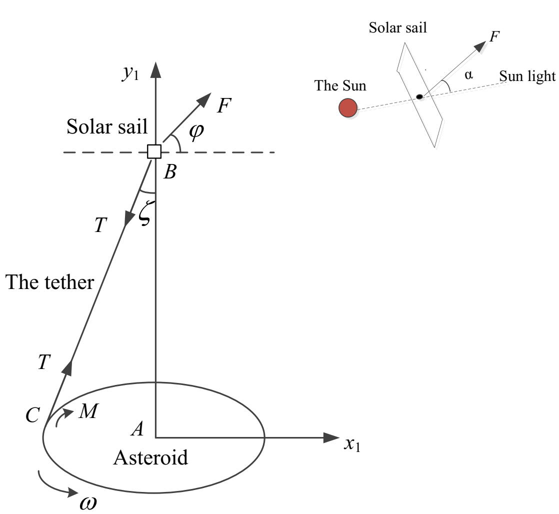

Fig. 1. The configuration of the tethered solar sail system.

2. Dynamic model

As shown in Fig. 1, the solar sail is connected with an asteroid by a nonelastic and massless tether. We assume that the solar sail moves to the equilibrium point of an asteroid and completes a connection with the asteroid. At the equilibrium point, the tether twining problem, which is caused by the relative orbit motion, is not need to be considered. Solar radiation pressure F acting on the solar sail is controlled in the Ax_1y_1 plane. Through the tether, the solar sail continually produces torque M which is opposite to the rotation direction of the asteroid. Torque M can decrease the rotation rate of the asteroid. In Fig. 1, φ denotes the angle between F and the Ax_1 axis. ζ is the angle between the direction of the tether and the Ay_1 axis. T is the tether tension.

From the reference (Hu, 2002), in the fixed coordinate system of an asteroid as shown in Fig. 2, the motion equation of a spacecraft can be expressed as follows

$$\begin{cases} \ddot{x} - 2\omega\dot{y} = \omega^2 x - \frac{\mu x}{r^3} + \frac{\partial U_2}{\partial x} \\ \ddot{y} + 2\omega\dot{x} = \omega^2 y - \frac{\mu y}{r^3} + \frac{\partial U_2}{\partial y} \\ \ddot{z} = -\frac{\mu z}{r^3} + \frac{\partial U_2}{\partial z} \end{cases} \tag{1}$$

where (x, y, z) is the position coordinate of the spacecraft in the rotating gravitational field of the asteroid. $r = \sqrt{x^2 + y^2 + z^2}$. ω is the spin velocity of the asteroid. μ is the gravitational constant of the asteroid. U_2 is the gravitational perturbation potential of the 2nd degree and order in the body-fixed frame. U_2 is expressed as follow:

$$U_2 = \frac{\mu}{r^3}\left[C_{20}\left(1 - \frac{3}{2}\cos^2\lambda_1\right) + 3C_{22}\cos^2\lambda_1\cos 2\lambda_2\right] \tag{2}$$

where C_{20} and C_{22} are spherical harmonic coefficients of an asteroid. λ_1 and λ_2 are the latitude and longitude of a spacecraft in the fixed coordinate system of an asteroid respectively.

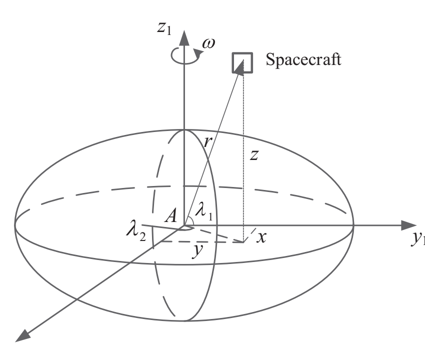

Fig. 2. The fixed coordinate system of the asteroid.