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Switched propulsion force libration control for the low-thrust space tug system

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ABSTRACT

The number of micro-satellites launched by commercial rockets and designed by universities and institutions is experiencing rapid growth, inevitably increasing the amount of the space debris of the same size. This paper adopts a low-thrust tethered space tug system to achieve debris deorbit. A switched low-propulsion force control method using only two constant-thrust modes to achieve both deorbit and libration control is presented. This kind of control method benefits from its robustness and low demand on the output accuracy of the thruster. The harmonic-like libration dynamics of the tethered space tug system around the local horizontal configuration is discussed and the stability of the control method is proved. Moreover, the sufficient condition for the switching sustainability is presented. Afterwards, the control effects of such a system are illustrated using numerical simulations. A modified control law to adapt practical demands shows the flexibility of the switching control methodology.

1. Introduction

As the space industry and technology develop rapidly, the number of expired artificial space vehicles in low Earth orbits (LEOs) explodes, leading to a more severe space environment. Diverse methods presented for space debris removal are being studied by plenty of scholars [1]. As for tethered satellite systems, the two most popular concepts for space debris removal are the tethered space tug (TST) system and the electrodynamic tether [2,3]. To achieve fast debris deorbit, the tethered space tug system is a better alternative because an electrodynamic tether requires a much longer tether and devices for electron collection and emission to generate a considerable electrodynamic force [4].

Great efforts have been made by researchers to reveal the complicated nonlinear dynamic characteristics [5–10] and devise ingenious control methodologies for tethered satellite systems [11–19]. Usually the control inputs to stabilize the tether libration are the tether length/rate or the tether tension. The propulsion force is preferred to be treated as an augmentation of the tension [20–22] rather than a sole control input due to the fact that thrusters providing variable propulsion force are difficult to manufacture and the output accuracy of the thrusters is hard to guarantee, which will surely affect the control efficiency. In addition, the propellant consumption needs to be considered as well. However, compared with other inputs, the propulsion force can generate a more considerable moment, which is propitious to damp the tether libration in a short time. For TST systems, in fact, the fuel consumption on the tug is inevitable. Meanwhile, the number of near Earth micro-satellites weighing from 10 kg to 100 kg launched by commercial rockets and designed by universities and institutions is experiencing rapid growth, inevitably increasing the amount of the space debris of the same size [23]. To deorbit such micro-satellites, low-thrust proposals are more suitable owing to the higher specific impulse and softer impact on tether [24].

In this paper, a switched low propulsion force control method using only two constant thrust modes is adopted to achieve both deorbit and libration control. This kind of control method benefits from its robustness and low demand on the output accuracy of the thruster, which is highly suitable and easy for engineering applications. The orientation of the thrust is confined to the opposite direction of the orbital motion to avoid the waste of fuel. The stability and design of switched systems or hybrid dynamical systems have been discussed by many foregoers [25–28], and the basic idea of switched systems is to orchestrate the switching between a family of continuous-time subsystems to achieve stabilization. Specifically, each of these subsystems is unnecessary to be stable. The fitness of this control method for a TST system comes from the harmonic-like in-plane and out-of-plane oscillations, as is discussed in Sec. 2, which will not diverge in a long period of time. The stability of this control method is proved in Sec. 3 with the robustness revealed. In fact, the demand on the output accuracy of the thruster can be loosened because the stability of the

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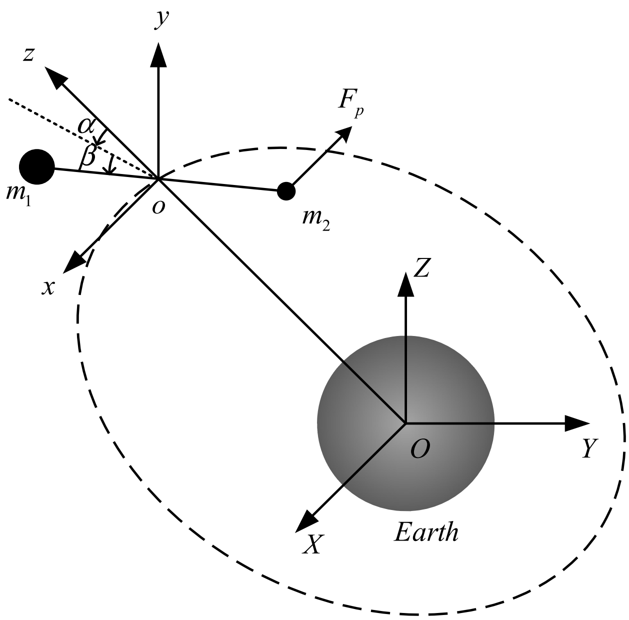

Fig. 1. Illustration of different coordinate systems.

controller only depends on the ratio between the two constant propulsion forces of which allowable range is sizable. In addition, once the values of the two constant thrusts are selected, the effect of the switching control is mainly determined by the switching time, which only relies on the current states of the system, forming another reason of the low demand on thrust accuracy. Some numerical results are given in Sec. 4 to show the competence and flexibility of the controller.

2. Equation of motion

Different kinds of dynamic formulations of a TST system were derived by many scholars based on different requirements. This paper focuses on the libration control of the tether, so the dumbbell assumption is adopted as in [29]. The coordinate systems used in this paper are illustrated in Fig. 1 with m_1 and m_2 standing for the debris and the main satellite platform respectively. The geocentric inertial frame $OXYZ$ is used to describe the orbit motion of the TST system, with the X axis pointing to the Vernal Equinox, the Z axis perpendicular to the equatorial plane pointing to the north and the Y axis constituting the right-hand coordinate system, while the orbit frame $oxyz$ is applied to describe the libration motion. The z axis points from the center of the Earth to the center of mass (COM) of the TST system and y axis is perpendicular to the orbit plane. The in-plane libration angle α and out-of-plane angle β are defined by the sequential y–x rotations from the orbit frame to the TST body frame, see Fig. 1.

For the orbit motion of the COM of the TST system, the Gaussian perturbation equations are applied as in [29]. On account of that the libration motion of a regular TST system is usually around the local horizontal, the in-plane angle α applied in [29] is replaced by $\tau_\alpha = \alpha - \frac{\pi}{2}$ and the dynamic equation for the libration motion is given as

$$\begin{aligned}
&\ddot{\tau}_\alpha + \ddot{\nu} - 2(\dot{\tau}_\alpha + \dot{\nu})\dot{\beta}\tan\beta - 3\mu r^{-3}\sin\tau_\alpha\cos\tau_\alpha = \frac{Q_{\tau_\alpha}}{\tilde{m}L^2\cos^2\beta} \\
&\ddot{\beta} + (\dot{\tau}_\alpha + \dot{\nu})^2\sin\beta\cos\beta + 3\mu r^{-3}\sin^2\tau_\alpha\sin\beta\cos\beta = \frac{Q_\beta}{\tilde{m}L^2}
\end{aligned} \tag{1}$$

where the reduced mass $\tilde{m} = \frac{m_1 m_2 + (m_1+m_2)m_t/3 + m_t^2/12}{m_{TST}}$ and $m_{TST} = m_1 + m_2 + m_t$ is the total mass of the tethered space tug system. Q_{τ_α} and Q_β are the corresponding generalized forces with respect to the in-plane motion and out-of-plane motion.

Usually, the attitude of the space tug can be well stabilized by the attitude control mechanism carried by itself. Therefore, it is a reasonable assumption that the propulsion force is the only contribution to the generalized forces and always align the $-x$ axis of the orbit frame. Then the expressions of Q_{τ_α} and Q_β are

$$\begin{aligned}
Q_{\tau_\alpha} &= -\frac{F_p(m_1 + m_t/2)}{m_{TST}} L\sin\tau_\alpha\cos\beta \\
Q_\beta &= -\frac{F_p(m_1 + m_t/2)}{m_{TST}} L\cos\tau_\alpha\sin\beta
\end{aligned} \tag{2}$$

If it is further assumed that the orbital angular acceleration $\ddot{\nu}$ can be neglected in a near circular orbit, after linearization, the equation for the libration becomes

$$\begin{aligned}
&\ddot{\tau}_\alpha + k_1\tau_\alpha = 0 \\
&\ddot{\beta} + k_2\beta = 0
\end{aligned} \tag{3}$$

where $k_1 = \frac{(m_1+m_t/2)}{\tilde{m}m_{TST}L}F_p - 3\mu r^{-3}$ and $k_2 = \frac{(m_1+m_t/2)}{\tilde{m}m_{TST}L}F_p + \dot{\nu}^2$. It is found that $k_2 > k_1 > 0$ when $F_p > 3\mu r^{-3}\tilde{m}m_{TST}L(m_1 + m_t/2)^{-1}$. Then both the out-of-plane motion and the in-plane motion are simplified to a harmonic vibration if the propulsion force is sufficiently large. However, the vibration frequencies of the in-plane motion and the out-of-plane motion are different due to that $k_1 \neq k_2$. This kind of dynamic performance will be used to prove the sustainability of the switching process presented in Section 3.

3. Switched propulsion controller design

Suppose the tug can provide propulsion forces in two different magnitudes $\underline{F}_p$ and $\overline{F}_p$, $\underline{F}_p < \overline{F}_p$. Two class K_∞ functions V_1 and V_2 are defined as follows to describe the in-plane and out-of-plane motions. Their sum, V, stands for the integral libration motion.

$$\begin{aligned}
V_1^n &= \tau_\alpha^2 + \frac{1}{k_1}\dot{\tau}_\alpha^2 \\
V_2^n &= \beta^2 + \frac{1}{k_2}\dot{\beta}^2 \\
V^n &= V_1^n + V_2^n
\end{aligned} \tag{4}$$

The superscripts $(1, 2, \ldots, n, \ldots)$ denote the switching sequence of the propulsion force. k_1 and k_2 are relevant to the thrust F_p as shown in Eq. (3). Denote $\overline{k}_1$ and $\overline{k}_2$ for the larger propulsion force $\overline{F}_p$ whereas $\underline{k}_1$ and $\underline{k}_2$ for the smaller one $\underline{F}_p$. It is appointed that the odd indices in Eq. (4) correspond to the smaller $\underline{F}_p$, $\underline{k}_1$ and $\underline{k}_2$ while the even indices correspond to the larger $\overline{F}_p$, $\overline{k}_1$ and $\overline{k}_2$.

Assume that the value of function V^n in the current switching interval is bounded and satisfies

$$V^n \le (1+\varepsilon)V_0^n = (1+\varepsilon)\left(V_{10}^n + V_{20}^n\right) \tag{5}$$

where $\varepsilon \ge 0$ is a real constant. The numbers 0 in the rear of the subscripts denote the initial values of the functions after the former switch. The switching law of the propulsion force is given as

$$n = \begin{cases} n+1, & \text{if } n \text{ is odd and } \tau_\alpha^2 + \beta^2 < \delta V^n \\ n+1, & \text{if } n \text{ is even and } \tau_\alpha^2 + \beta^2 > (1-\delta)V^n \end{cases} \tag{6}$$

where $0 < \delta < 1$ is a real constant. For the case that n is odd, the value of the function V_0^{n+1} is