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Analysis of the effect of attachment point bias during large space debris removal using a tethered space tug

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ABSTRACT

Space debris occupies a valuable orbital resource and is an inevitable and urgent problem, especially for large space debris because of its high risk and the possible crippling effects of a collision. Space debris has attracted much attention in recent years. A tethered system used in an active debris removal scenario is a promising method to de-orbit large debris in a safe manner. In a tethered system, the flexibility of the tether used in debris removal can possibly induce tangling, which is dangerous and should be avoided. In particular, attachment point bias due to capture error can significantly affect the motion of debris relative to the tether and increase the tangling risk. Hence, in this paper, the effect of attachment point bias on the tethered system is studied based on a dynamic model established based on a Newtonian approach. Next, a safety metric of avoiding a tangle when a tether is tensioned with attachment point bias is designed to analyse the tangling risk of the tethered system. Finally, several numerical cases are established and simulated to validate the effects of attachment point bias on a space tethered system.

1. Introduction

With the increasing level of human activities in space, the problem of space debris occupying valuable orbital resource is inevitable. Despite the enactment of debris mitigation measures and improved cognition of orbiting space debris, the ability to scavenge large space debris located along the operating orbit is still a major issue [1]. Large debris (spent rocket stages, defunct satellites, etc.) is more prone to collisions, which can produce tens of thousands of pieces of new debris [2]. Therefore, it is urgent to safely clear large abandoned targets to ensure the safety of spacecraft operating in orbit [3].

The use of a tether for debris removal has been proposed [4] with the advantages of wider operating ranges and low costs. Many scholars have presented in-depth studies regarding the application of tethers; such studies mainly include the two categories of momentum exchange tethers and electrodynamic tethers [5]. The concept of active debris removal (ADR) has been proposed to safely remove high-risk debris, such as large massive debris [6–8], aiming to de-orbit the predetermined debris captured by a dedicated tethered spacecraft via active thrust. A notable project called ROGER (Robotic Geostationary Orbit Restorer) was developed by the ESA (European Space Agency) [9,10] to capture and de-orbit a redundant GEO (geostationary orbit) satellite using a tethered net or mechanical claw. Specifically, once the debris is captured by a manipulator, such as a harpoon, a mechanical hand or a net, a tethered spacecraft system (TSS) is established to achieve de-orbiting of a passive, non-cooperative, possibly spinning target.

However, the flexibility of the tether leads to several technical challenges regarding the stability of the TTS and increases the difficulty in control system design. In recent years, some researchers have studied the stability of the de-orbit system and improved some novel control approaches [11–19]. Nevertheless, especially for large spinning debris, the angular momentum of debris can also have a strong effect on active spacecraft, which may induce twining of the tether and even result in the loss of control of the system. Therefore, some achievements in dynamic analysis of the attitude of large debris have recently been proposed [20–23]. In Ref. [20], a simplified model of a tethered system is set using the Lagrange formalism to prove that the properties of the tether can affect the oscillation of the passive satellite. In addition, the slackness of the tether is of high risk of inducing tether tangling. Subsequently, flexible appendages are further taken into consideration in Ref. [21]; the choice of the stiffness of the tether was found to be important to avoid resonance between the tether and debris. Based on early work [20], Aslanov and Yudintsev [22] modelled the system using the Newtonian approach to further study additional effects, such as the thrust level,

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orbital motion and atmospheric drag on system. In addition, the initial angle between the tether and vector from the mass of the debris to the attachment point is involved in the simulation case, which significantly affects the amplitude of the oscillation of passive debris. Moreover, several simulation cases are also studied in Ref. [23], which proposes a novel sub-tether structure to reduce the oscillation of the debris. Although the effect of many parameters mentioned above has been studied on a tethered system, attachment point bias is always neglected entirely to simplify the model or is simplified in the simulation with the variation of other parameters. In fact, attachment point bias can change the acting point and arm of tether tension on debris, which easily occur in actual operation during the capture phase. Therefore, attachment point bias can significantly influence the motion of the debris, even leading to a crippling tangle. However, the specific effects of the bias have hardly been studied, making it significant to study the effect of attachment point bias on the motion of debris with a tangling risk. Here, the novelty of the work is as follows. First, the effect of different biases of the attachment point on the motion of debris relative to the tether with the tangling risk is analysed. Next, the safety metric for avoiding a tangle when the tether is tensioned is designed to analyse the tangling risk of the system with attachment point bias. Finally, several simulation cases are implemented to validate the effect of attachment point bias with the safety metric.

This paper includes five main sections. In Section 2, the effect of attachment point bias on the motion of debris relative to the tether is analysed based on a dynamic model established using a Newtonian approach. Based on that model, in Section 3, the safety metric of avoiding a tangle when the tether is tensioned with attachment point bias is designed to analyse the tangling risk of the tethered system. Next, several numerical cases are implemented to analyse the variation of the relative motion between the debris and tether caused by different biases of the attachment point in the post-capture phase in Section 4. Finally, conclusions are summarized in Section 5.

2. Analysis of the effect of attachment point bias on the motion of debris relative to the tether

2.1. Assumptions and reference frames

As shown in Fig. 1, large space debris (non-cooperative, nonfunctional, passive objects) is regarded as a rigid body, hereafter referred to as a target, and the active space tug is considered to be a particle. A visco-elastic tether is used to connect the space tug to the target. In addition, the active de-orbit force of the system is provided by a rocket thruster on the space tug.

We focus on the attitude of large passive debris (hereinafter referred to as the target) relative to the tether. The mass of the visco-elastic tether is far less than the end bodies and can be neglected. In addition, bending of the tether is also ignored when the tether is tensioned because of its short length. Moreover, the short-time consumption of fuel is neglected as well.

Based on the assumptions mentioned above, the following reference frames (shown in Fig. 1) used in describing the system are introduced:

(1) The Earth centred inertial reference frame $\Re_I$, the origin of which coincides with Earth's centre O_e, $\overrightarrow{O_e x_e}$ points to the vernal equinox, $\overrightarrow{O_e z_e}$ is perpendicular to Earth's equatorial plane, and $\overrightarrow{O_e y_e}$ is determined afterwards using the right-hand rule.
(2) The local orbital coordinate frame $\Re_O$, its origin attached to the system centroid O, $\overrightarrow{O z_o}$ points to O_e, $\overrightarrow{O x_o}$ is perpendicular to $\overrightarrow{O z_o}$ in the orbital plane and lying behind the target, and is $\overrightarrow{O y_o}$ determined afterwards using the right-hand rule.
(3) The body fixed frame of target $\Re_T$, its origin coincides with the target centroid O_t, $\overrightarrow{O_t x_t}$, $\overrightarrow{O_t y_t}$ and $\overrightarrow{O_t z_t}$, which coincide with three principal inertial axes, respectively, conforming to the right-hand rule.

2.2. Analysis of the effect of the attachment point bias on a space tethered system

As shown in Fig. 1, the space tethered system consists of a space tug, a massless visco-elastic tether and a large passive target. The motion of the space tug and target is considered in $\Re_I$ with the following equations:

$$m_c\ddot{\boldsymbol{r}}_c = -\mu m_c \boldsymbol{r}_c / r_c^3 + \boldsymbol{F}_{th} - \boldsymbol{T} \tag{1}$$

$$m_t\ddot{\boldsymbol{r}}_t = -\mu m_t \boldsymbol{r}_t / r_t^3 + \boldsymbol{T} \tag{2}$$

where m_c and m_t are the masses of the space tug and target, respectively; $\boldsymbol{r}_c$ and $\boldsymbol{r}_t$ are the position of the space tug and the target in $\Re_I$ respectively; $\boldsymbol{F}_{th}$ is the thruster force on the space tug; and $\boldsymbol{T}$ is the tension vector along the tether from the attachment point pointing to the space tug.

Thus, the motion of the system centroid can be described as

$$\boldsymbol{r} = \eta_c \boldsymbol{r}_c + \eta_t \boldsymbol{r}_t \tag{3}$$

$$\dot{\boldsymbol{r}} = \eta_c \dot{\boldsymbol{r}}_c + \eta_t \dot{\boldsymbol{r}}_t \tag{4}$$

where $\boldsymbol{r}$ and $\dot{\boldsymbol{r}}$ are the position and velocity of the system centroid and $\eta_c = m_c/m$, $\eta_t = m_t/m$ and m are the total mass of the system, i.e. $m = m_c + m_t$.

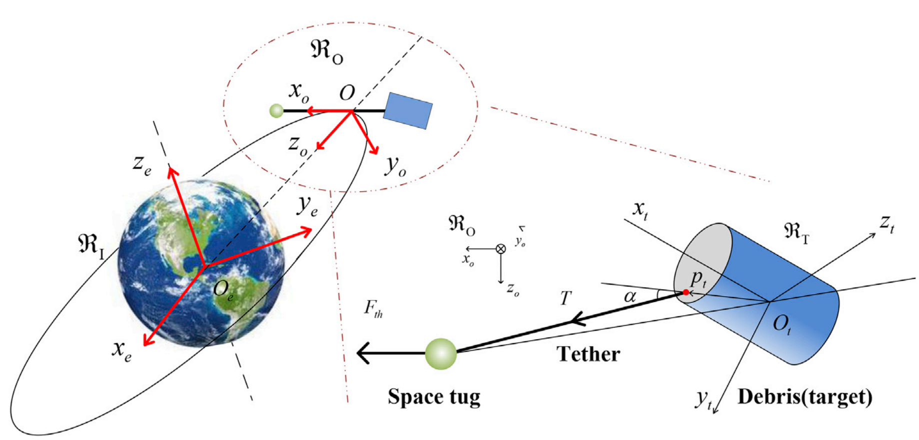

Fig. 1. Space tethered system in active debris removal.