Acta Astronautica 104 (2014) 91–98

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Behavior of tethered debris with flexible appendages

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ARTICLE INFO

Article history:
Received 29 January 2014
Received in revised form
21 July 2014
Accepted 23 July 2014
Available online 30 July 2014

Keywords:
Active debris removal
Tether
Space tug
Relative motion
Flexible appendages
Vibrations

ABSTRACT

Active exploration of the space leads to growth of a near-Earth space pollution. The frequency of the registered collisions of space debris with functional satellites highly increased during last 10 years. As a rule a large space debris can be observed from the Earth and catalogued, then it is possible to avoid collision with the active spacecraft. However every large debris is a potential source of a numerous small debris particles. To reduce debris population in the near Earth space the large debris should be removed from working orbits. The active debris removal technique is considered that intend to use a tethered orbital transfer vehicle, or a space tug attached by a tether to the space debris. This paper focuses on the dynamics of the space debris with flexible appendages. Mathematical model of the system is derived using the Lagrange formalism. Several numerical examples are presented to illustrate the mutual influence of the oscillations of flexible appendages and the oscillations of a tether. It is shown that flexible appendages can have a significant influence on the attitude motion of the space debris and the safety of the transportation process.

1. Introduction

The first Russian Sputnik satellite that was launched in 1957, stayed in orbit for 3 months only. In the last half century more than six thousand spacecraft were launched to the Earth orbits and many of them remain in orbit. There are more than 15,000 large objects on the orbits around the Earth. Only 7% of these are active spacecraft, 17% are nonfunctional spacecraft and 13% are orbital stages of the rockets [1]. All these objects are tracked and an active spacecraft or a space station can avoid collision with such objects. Collisions of the large space debris with other debris can significantly increase numbers of the small debris on the Earth orbit. The Fengyun 1C anti-satellite test [2] and the Cosmos-Iridium collision [3] created over 5000 small objects [4]. The debris cascade effect described by Kessler [5] has begun to occur. Several orbits can be dangerous for the new missions therefore large debris should be removed. Removal of five or more large debris per year can reduce the debris population [6].

Over the last years several active debris removal methods were developed [7–14]. In Fig. 1 one of the possible classifications of the active debris removal is shown. There are three types of the connection between a space tug and a space debris: flexible connection, rigid connection and distant interaction. The last case applies to the techniques based on the idea of thrusting a space debris by irradiating it with an ion beam [15]. Rigid connection between a space tug and a debris can be realized by robot arm. The flexible connection can be provided by a tether attached to the space debris.

In our opinion, the tethered transportation with the pulling space tug has the following advantages over the rigidly connected space tug and space debris:

- Lower requirements for the tug's control system, because of natural stability of the pull scheme [1].

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http://dx.doi.org/10.1016/j.actaastro.2014.07.028
0094-5765/

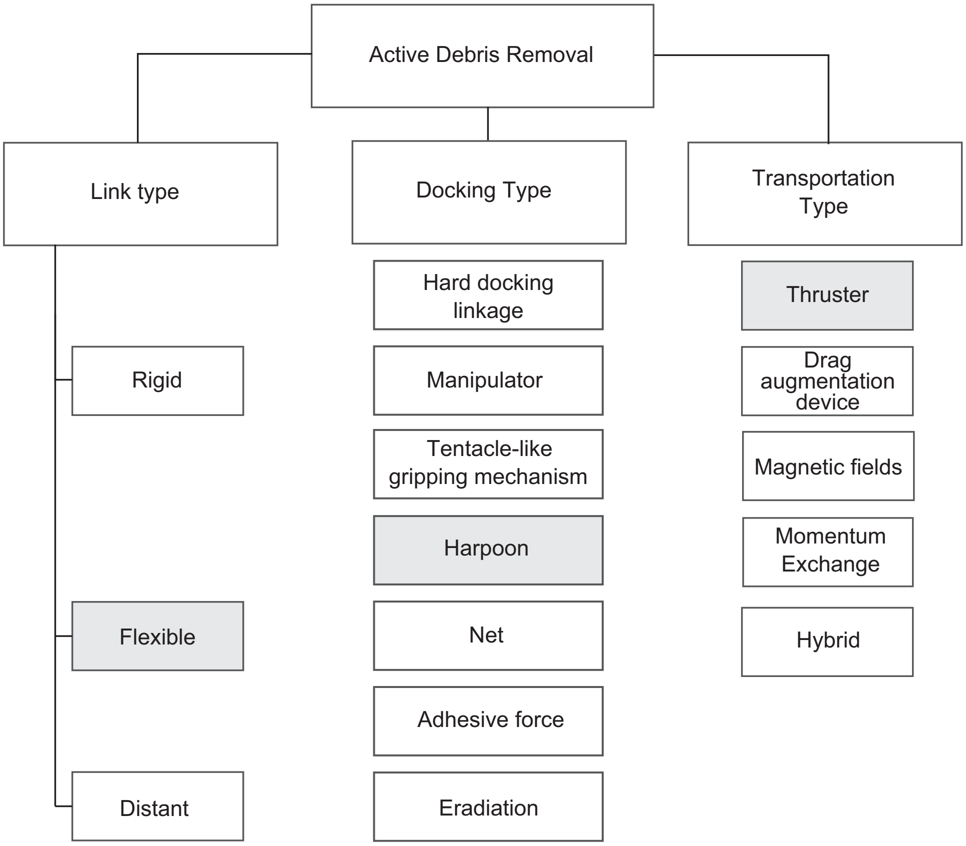

Fig. 1. Active debris removal classification.

- Transportation is safe for the space tug: in the case of breaking of connection with the debris the transportation attempt can be repeated.

The active debris removal mission can be divided into several stages specified by the motion pattern of the space tug relative to the space debris [7]:

1. Placing the space tug into orbit.
2. Far-range rendezvous between the space tug and the debris.
3. Rendez-vous phase.
4. Mechanical interfacing (docking, grapping, etc.).
5. De-tumbling and orientation of the space debris.
6. Thruster-burn phase.
7. De-orbitation (post-burn) phase.
8. Enter to the atmosphere.

Each stage requires a different mathematical model. Note that mathematical models for the steps 1–3, 7 and 8 are well known. To analyze these steps do not require the creation of any new models in addition to the existing models of the orbital motion of the spacecraft.

Post-burn phase is considered in [16–18] where thruster input shaping techniques are discussed to reduce the post-burn relative motion between space tug and space debris. The motion of the tug–tether–debris system as a material point, assuming stationarity of the relative motion of the tug and the debris for the stage 7, can be described by differential equations in the osculating parameters [19]. The atmospheric entry can be analyzed using the mathematical models presented in [20,21].

The choice of the active debris removal technique depends on the properties of the space debris. Ref. [1] notes that there are two types of the space debris: spacecraft or orbital stages. Orbital stages are more “comfortable” for the deorbit, because they do not have large appendages (solar panels, antennas).

The removal of passive spacecraft with flexible appendages is a more complex problem. The possibility of a vibration of flexible appendages should be considered that may lead to the destruction of the spacecraft and the emergence of an even greater number of small fragments.

In this paper we draw attention to the stage 6 of the active removal of a space debris with flexible appendages. The aim of the present work is to derive a mathematical model to perform a research on the influence of flexible appendages of space debris (passive spacecraft) to the initial phase of the deorbit process. We consider the simple impulsive burn of the tug's thrust. As noted above, input shaping techniques can be used to reduce the post-burn relative motion between space tug and space debris [17]. An alternative solution to remove collision potential is the use of post-burn manoeuvre of the space tug after detaching the tether to establish a safe relative orbit of the tug.