International Journal of Research Available at https://edupediapublications.org/journals

e-ISSN: 2348-6848
p-ISSN: 2348-795X
Volume 05 Issue 7
March 2018

Momentum-Exchange Tether Propulsion System for Propellantless Orbital Manoeuvres: A Review

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Abstract- The conventional chemical propulsion systems, while delivering numerous advantages, are not much efficient for deep space missions owing to their dependence on quantity of stored chemical propellants and calorific value of the propellant composition. Even the most energetic combination of fuel and oxidizer is able to deliver a maximum specific impulse just in the range of 450-550s. Such low range of specific impulse of chemical propulsion systems make them unsuitable for missions extending over longer periods of time. Though other propulsion systems like electrical and nuclear propulsion systems deliver specific impulse in the magnitudes of thousands, the thrust generated by such efficient engines is normally in either millinewtons or micronewtons. Tether propulsion is one promising type of system which is essentially propellantless and thus eradicates the inherent limitations imposed on the propulsion system resulting from the dependency on propellant's quantity and calorific value. This study briefly reviews the history, working principle and operation of Momentum-Exchange Tether Propulsion Systems. A brief review regarding various types of tethers and tether materials under contemporary research have also been carried out in this study.

Keywords- Tether Propulsion; Space Tethers; Momentum-Exchange Tether Propulsion Systems; Orbital Manoeuvring; Propellantless Propulsion.

1. Introduction

The concept of tether propulsion system utilizes very strong cables, technically known as 'tethers' or 'space tethers' [1]. Tethers can greatly assist in initiating and completing launch and/or in altering the orbital characteristics of a spacecraft or a satellite. These tethers have extreme tensile strength and may be used to change the orbit of a spacecraft or satellite [2]. Such manoeuvring is obtained by utilizing the interaction with the magnetic field of a celestial body or through exchanging momentum between objects [3].

The tether propulsion system may provide a propulsion technique which is significantly less expensive than conventional flight vehicles using rocket engines [4]. Tether propulsion extract power from the near-Earth space environment, facilitating the transfer of energy and momentum between two given objects. Since tether propulsion draws its power from space environment, it is fundamentally a comparatively inexpensive, efficient, reusable and propellantless propulsion technique [5]. It also has the potential and capabilities to turn space tethers into "space tugboats" allowing the efficient relocation of flight vehicles and payloads. Space tethers enable propellantless increase or decrease of spacecraft's orbital energy and satellite's orbits by eliminating the usage of heavy, costly and traditional chemical propulsion systems [6].

Russian scientist 'Konstantin Tsiolkovsky' in 1895 first conceived the concept of space tethers as he became fascinated by Eiffel Tower of Paris, France. He theorized an immensely taller tower reaching into space and with a 'celestial castle' at the apex. He also fantasized a free-floating, spindle-shaped tower reaching from near the Earth's surface and extending beyond the geosynchronous orbit. Excess centrifugal force on the part of the tower extending beyond the geosynchronous altitude would support its tension. These were the first of the series of 'space elevator' concepts having a tether placed in geosynchronous orbit and reaching all the way down to Earth's surface. He proposed a tall tower extended into deep space and held in position by the rotation of the Earth. However, construction and deployment of such massive tethers were far from reality at that time due to technological limitations [7].

Giuseppe Colombo in 1947 theorized about an extended tether to support a satellite system (TSS) to investigate plasma physics and the fundamentals of generation of electricity in upper atmosphere [8]. Later, another Russian 'Yuri Artsutanov' mentioned about a tensile cable to be deployed from a geosynchronous satellite and reaching towards the Earth's surface and extended upwards away from the orbit, thus keeping the cable in balance. Issac et al. (1967) briefly analysed material strength requirements for the realization of tether propulsion system concept [9]. Moravec

(1977) concluded through his investigations that a non-synchronous spinning tether would eliminate few of the inherent problems of the extended hanging tethers [10]. Carroll (1986) highlighted the advantages of swinging and scarcely spinning systems [11]. Tiesehausen (1984) wrote a history of these concepts and of their more modest derivatives [12]. Other early tether protagonists include ‘Ivan Bekey’, Mario Grossi’ and ‘Chriss Rupp’. Their determinations steered the development towards a series of 4 orbital flight tests of the tethers between 1992 and 1994 followed by 3 more tests during 1996 and 1997 [13-15].

Tsiolkovsky and few others hypothesized about a huge structure which could be constructed that would extend from the Earth’s surface to altitudes above geostationary orbit and could be used as a convenient and effective means of transporting objects from Earth and into deep space. These apparently implausible philosophies served as the foundation for the concept of contemporary space tethers and tether propulsion systems.

2. Momentum Exchange Tether System

In a Momentum-Exchange Tether Propulsion System, a long, thin, high-strength cable is positioned in geosynchronous orbit and is allowed to rotate around a central body [16]. In Momentum-Exchange Tether Propulsion System, the tether is used to connect two objects in space so that one transfers momentum and energy to the other. The distance separating these two objects would lead to the difference in the gravitational force acting at the two locations which will cause both of the objects to be pulled apart. This phenomenon is termed as ‘Gravity Gradient Force’. The tether can be allowed to move at a controlled rate, pulled due to the tension resulted by the Gravity Gradient Force [17]. Once the tether is positioned and in the absence of any unbalanced forces acting on the tether, it will attain an equilibrium having vertically aligned orientation as shown in Figure 1.

Significant speeds (~1-3 km/s) would be experienced at tips of this high speed rotating, spinning momentum-exchange tether. Stress tolerances would limit the maximum speed experienced by the tether which can be prominently augmented if the tether has a thicker middle cross section while having a lighter, thinner at the tether tips [18].

If the tether facility is placed in an elliptical orbit and its rotation is timed so that the tether is oriented vertically below the central body and swinging backwards when the facility reaches perigee, then a grapple assembles located at the tip of the tether can rendezvous with and can capture a payload moving in a lower orbit. The tether can release the payload after completing half of the rotation, tossing payload into a higher energy orbit. Owing to the fact that when the tether captures and releases the payload, it transfers some of its own orbital energy and momentum to the payload, this concept is called as Momentum-Exchange Tether Propulsion System. The transference of energy and momentum from the tether to the payload results in a drop in the tether facility’s apogee [19-20].

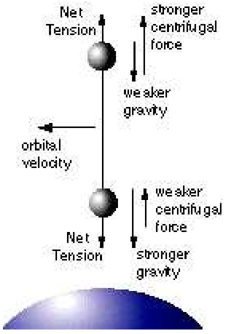

Figure 1: Vertically alignment of the tether owing to balanced forces

This system can also be utilized to deaccelerate incoming spacecraft or satellite, which in turn would upsurge the tether facility’s momentum and energy. If the average momentum gained from inward traffic equals to the momentum decreased due to outward traffic, there would be no net loss of energy and momentum of the tether facility [21].

3. Working Law of Momentum Exchange Tether System

Momentum-Exchange Tether Propulsion System works on the law of conservation of Inertia or Newton’s second law of motion. This is also implied for a rotating system where the angular momentum is constant, which is mathematically defined as follows:

$$L = \int \vec{r} \times \dot{\vec{r}}\,dm \qquad (1)$$

Where $\vec{r}$ is the position in space, $\dot{\vec{r}}m = \vec{p}(\vec{r})$ is the momentum so $\dot{\vec{r}}dm = d\vec{p}(\vec{r})$ is the momentum element with m as the mass and $\dot{\vec{r}}$ as the velocity. M is the total mass of the system. This means that rotational speed of a system can be altered by changing its mass distribution [22].

Newton's first law of motion states that a system in the absence of any kind of external force will keep its speed constant. While discussing about trajectories and orbit, the above statement can be rephrased and it could be said that the trajectory or orbit of the body would remain constant. To alter the centre of mass of the system, an external force will have to be exerted on it. This implies that a rotating tether will rotate about its centre of mass, thereby not altering the orbit or trajectory of the mass centre. Gravitational forces acting on the system have been neglected in this theory [23].

4. Tether/Payload Rendezvous

Tether/Payload rendezvous is essentially a completely different and specific manoeuvre. There would be no momentum to exchange between the tether and payload if they were to match orbits by having identical positions, velocity and acceleration. Therefore, tether/payload rendezvous can be only realised by matching the velocity and position of the tether tip with that of the payload at a given point in space and time. Acceleration is avoided to be identical in order to positively exchange momentum between tether facility and the payload. This is achieved by controlling the angular rotation rate of the tether in such a way that the tether tip's velocity is the difference between the orbital velocity of the tether and the payload. Consider the tether like a wheel rolling around the orbit of the payload where the tip of the tether is like a point on the wheel and thus the tip makes contact with the payload only at a given instant of time [24-25].

From the viewpoint of the payload, the tether's tip descends swiftly from above, comes to a stagnation and then ascends rapidly. During that moment of zero relative velocity, contact is required to be made between the tether tip and the payload. So while traditional orbital rendezvous techniques take place over a longer duration of time, tether/payload rendezvous is to happen instantaneously while simultaneously being tolerant of any substantial position and velocity errors [26].

5. Tether Types

Tethers having a constant cross-section are called as cylindrical tethers while tethers with a varying cross-section are called as tapered tethers. The maximum sustainable velocity, called as critical velocity, V_c, for a spinning cylindrical tether without any payload attached to its tip is limited by its material properties and can be mathematically expressed as:

$$V_c = \sqrt{\frac{2\sigma}{\rho}} \qquad (2)$$

Where, σ and ρ is the ultimate strength and the mass density of the tether material, respectively. A more accurate approach is to adopt a ratio $\sigma^* = \sigma/f$ where $f>1$ is the strength safety factor. The ΔV that a cylindrical tether can deliver, therefore, is restricted. For example, 'Spectra 2000' has a V_c of 2.6 km/s with $\sigma = 3.25X10^9$ N/m^2, $\rho = 970$ kg/m^3 and a safety factor of 1 (no safety margin) while have a V_c of 1.96 km/s with a safety factor of 1.75 [27].

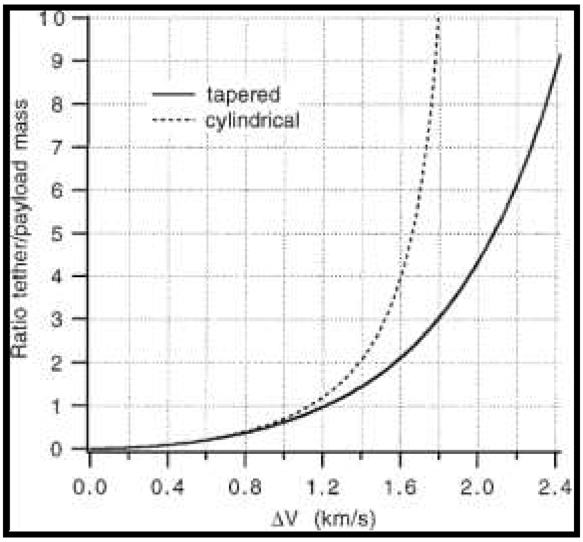

Figure 2: Tether/payload mass ratio for different cross-section of tethers

Since the hub of the tether experiences maximum stress during its operation, it would be efficient to taper the tether thereby saving tether mass and eradicating the constraint on the maximum sustainable ΔV. The mass of a tapered tether with a constant stress distribution would be a function of tip mass (i.e. payload, M_{PL}) and is mathematically expressed as follows:

$$M_{Tether} = M_{PL}\frac{V}{V_c}\exp(\frac{V^2}{V_c^2})erf(\frac{V}{V_c})\sqrt{(\pi} \qquad (3)$$

Where, V and $erf(V/V_c)$ is the tip velocity and the error function, respectively. Figure 2 represents and compare the tether/payload mass ratio for a cylindrical and a tapered tether of the same material (Spectra 2000) having a safety factor equal to 1.75. It can be observed from Figure 2 that tapered tether, essentially is lighter than a cylindrical tether especially for ΔV > 1km/s. Concurrently, it is evident from Figure 2 that ΔV imparted by a tapered tether is not restricted by the strength-to-density ratio of the material [28].

6. Tether Materials

The tether's characteristics velocity is a function of the material's strength-to-density ratio. The enhancement achieved in this ratio during the past decades provides an indication of future tendencies and the probable amplification in the magnitudes of the tether characteristics velocity in the near future.

Strength-to-density ratio of the tether material can be categorised into two distinct eras during this century: a) the metal era before 1960, with a gentle upsurge in the strength-to-weight ratio; and, b) the carbon fibre era after 1960, with a substantial growth in the strength-to-weight ratio. These improvements might seem intense but they would be completely eclipsed if materials like 'Fullerenes' come on line for the construction of long tethers. In laboratory, 'Fullerenes' has demonstrated a strength-to-density ratio almost two orders of magnitude higher than Spectra 2000. However, the samples produced and tested were only a few microns long but several attempts are underway at making this material suitable for forming space tethers [29].

The other materials proposed for use in tether facilities are 'Kevlar', 'Ultra High Molecular Weight Polyethylene', 'Carbon Nanotubes', 'M5 Fibre' and 'Diamond'. One material that has shown great potential is 'M5 Fibre'. It is a synthetic fibre and is lighter than 'Kevlar' or 'Spectra 2000'. According to the article titled 'The Lunar Space Elevator (2005), an 'M5 Fibre' ribbon 30mm wide and 0.023mm thick would be able to support 2000kg on lunar surface. It would also be able to hold 100 cargo vehicles each with a mass of 580kg, evenly spaced along the length of the tether. Other materials that could be used are 'T1000G Carbon Fibre' or 'Zylon'. All of these materials have breaking lengths of several hundred kilometres under normal 1g conditions (~9.807 m/s^2) [30].

7. Concluding Remarks

Momentum-exchange tether propulsion systems have shown to at least theoretically allow for quick, elegant and cost-effective raising and lowering technique for spacecraft and satellites. Momentum-exchange tether propulsion systems may also prove very useful in deorbiting malfunctioned satellites or spent stages and have a lot to contribute in future space activities. As the momentum-exchange tether propulsion systems do not consume any propellant, they are able to provide very large ΔVs with very small total mass, significantly reducing costs for missions that require high ΔV manoeuvres such as formation flying, low-altitude station keeping, orbit corrections and end-of-mission deorbit.

Momentum-exchange tether propulsion systems can be used in deep space missions where the satellite with higher orbital energy can drag the satellite with lower orbital energy through a planet's atmosphere for sample collection or even land the low energy satellite or rover on to the surface of any airless celestial body, such as asteroid or moon. Momentum-exchange tether propulsion systems provide an inexpensive way for space manoeuvres and may therefore be start of a new revolution in space propulsion. Owing to its inherent advantages, momentum-exchange tether propulsion systems and tether technology has unlocked thrilling possibilities for propellantless spacecraft propulsion.

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