Acta Astronautica 148 (2018) 268–275

Contents lists available at ScienceDirect

Acta Astronautica

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

Electric sail space flight dynamics and controls

Carlos Montalvo[a,*], Bruce Wiegmann[b,**]

[a] College of Engineering, University of South Alabama, 150 Jaguar Dr. Mobile, 36688, AL, USA
[b] NASA Marshall Space Flight Center, Huntsville, AL, USA

A B S T R A C T

This paper seeks to investigate the space flight dynamics of a rotating barbell Electric Sail (E-Sail). This E-Sail contains two 6U CubeSats connected to 8 km tethers joined at a central hub. The central hub is designed to be an insulator so that each tether can have differing voltages. An electron gun positively charges each tether which interacts with the solar wind to produce acceleration. If the voltage on each tether is different, the trajectory of the system can be altered. Flapping modes and tension spikes are found during many of these maneuvers and care must be taken to mitigate the magnitude of these oscillations. Using sinusoidal voltage inputs, it is possible to control the trajectory of this two-body E-Sail and propel the system to Near-Earth-Objects or even deep space.

1. Introduction

The Electric Sail (E-Sail) is a relatively new concept of advanced in space propulsion. This technology has the potential to provide propellant-less propulsion throughout the solar system. An electric sail deploys multiple long (20 km) tethers that are positively charged. The solar wind interacts with the tethers to provide propulsion. Based on the E-Sail's characteristic acceleration, the E-Sail can reach the Heliopause region in 10 years. A solar sails characteristic acceleration puts a solar sail in the Heliopause region in 20 years which can be compared to chemical rockets which is 24 years. The only spacecraft to reach the Heliopause region is the Voyager 1 and 2 spacecraft which reached the Heliopause region in 36 years. The increase in performance from a solar sail to an E-Sail lies in the growing sheath width of the electric sail which grows with distance from the sun. As such, an E-Sail will continue to accelerate to 20 AU as opposed to only about 5 AU with a solar sail.

Initial studies on E-Sails were completed by Janhunen and Mengali which created a mathematical model of the thrust produced by the solar wind [1], [2]. Much work has been done in the area of thrust generated by an E-Sail [3] but the models used were simple in that the system was already operating in steady state. The barbell E-Sail program poses numerous dynamics and controls problems due to flexible modes in the tether and elastic forces encountered in the tether as well as the multi-body dynamics from having two separate spacecraft. The Technology Demonstration Mission (TDM) simulated here includes two 6U CubeSats connected to a 16 km tether. The satellite initially de-tumbles and then separates both 6U CubeSats. The tether is then deployed. An electron gun is fired to positively charge the tether to interact with the solar wind to create propulsion. This propulsion must be counter-balanced by spinning the entire system. Thus, the entire system must undergo complex deployment and spinning as well as controlling the system by solely using thrust produced by the positively charged tether.

Previous work has been done in the area of tether deployment with many designs centered around using gravity gradients [4] to deploy the two spacecraft and then use a type of mechanical brake [5] or barber-pole [6] to halt the deployment of the tether. The YES2 satellite program utilized the gravity gradient of the Earth to deploy a small payload to re-enter the Earth's atmosphere [4]. The small payload was deployed with a long tether and then subsequently cut so the small payload could re-enter the atmosphere. This project utilized a barber-pole to slow the speed of the payload. The work done by Iki et al., involved deploying an electrodynamic tether for removal of large space debris. During deployment a small amount of friction was modeled. Once the tether reaches a critical length, a brake is deployed to increase the force on the secondary payload [5]. A comprehensive review of tether deployment has been put together by Yi et al. [7].

The second problem of in space tether control has been investigated in great detail as well. Chen et al. has put together a comprehensive review of tether attitude and motion control [7]. Work on rotational tethers has been conducted including the work by Modi et al.; however, this project involved the spacecraft rotating along the axis of the tether rather than orthogonal like the E-Sail [8]. Work that directly relates to E-Sail control has been performed quite recently by Janhunen [9], [10]. All of this work however has been performed using analytic solutions of rigid body systems. The work presented here establishes an E-Sail

---

[*] Corresponding author. Department of Mechanical Engineering, USA.
[**] Corresponding author. ED 04, NASA, MSFC, USA.
E-mail addresses: cmontalvo@southalabama.edu (C. Montalvo), bruce.m.wiegmann@nasa.gov (B. Wiegmann).

https://doi.org/10.1016/j.actaastro.2018.05.009
Received 11 December 2017; Received in revised form 13 April 2018; Accepted 3 May 2018
0094-5765/ Published by Elsevier Ltd on behalf of IAA.

Nomenclature

$\mathbf{H}_i$	relationship matrix of Euler angle derivatives to body angular velocity components of spacecraft i
I_i	moment of inertia matrix of spacecraft i taken about the mass center in the body frame($kg - m^2$)
I_{sp}	specific impulse of the satellite thrusters (sec)
L_i, M_i, N_i	components of the total moment applied to spacecraft i in body frame(N-m)
m_i	mass of spacecraft i (kg)
p_i, q_i, r_i	components of the mass center angular velocity vector in the body frame of spacecraft i (rad/s)
$\vec{r}_{AB}$	position vector from a generic point A to a generic point B (m)
$\mathbf{T}_{AB}$	generic transformation matrix rotating a vector from the frame B to frame A
u_i, v_i, w_i	components of the mass center velocity vector in the body frame of spacecraft i (m/s)
$\vec{V}_{A/B}$	velocity vector of a generic point A with respect to frame B (m/s)
x_i, y_i, z_i	components of the mass center position vector in the inertial frame of spacecraft i (m)
X_i, Y_i, Z_i	components of the total force applied to spacecraft i in body frame(N)
X_{Wi}, Y_{Wi}, Z_{Wi}	total weight force applied to spacecraft i (N)
φ_i, θ_i, ψ_i	Euler roll,pitch, and yaw of spacecraft i (rad)

dynamic model that contains a combined multi-body satellite model and a flexible tether. The model also includes an electric propulsion model. This article seeks to describe the dynamics of spinning the E-Sail and applying propulsion to the satellite by charging the tether. The article begins with a comprehensive dynamic model description and ends with an analysis of flexible modes and control modes.

2. E-Sail simulation tool

The mathematical model used here begins with the translational dynamics of the satellite using inertial coordinates to simplify the equations of motion. The satellite is assumed to be a rigid body using quaternions to parameterize orientation. Thrusters are placed on board the satellite which imparts forces and torques to control translational speed and angular velocity of the satellite. Each satellite is connected to a tether which is simulated using a visco-elastic tether bead model. Each tether is connected to a central insulated confluence point which is modeled as a three degree of freedom system. Insulation at the confluence point allows each tether to attain a different voltage potential to turn the E-Sail. Furthermore, if a hub and spoke E-Sail with 4 or even 8 satellites is simulated in the future, all satellites can be modeled with a single tether each connecting to this central confluence point. The model here describes the barbell E-Sail with two satellites and two tethers. Fig. 1 shows each component of the dynamic model. Note that the shape, number of beads and connection point on the CubeSats are irrelevant to the actual model simulated. The image shown below is a crude representation of an example two satellite E-Sail. The number of beads and connection point on each satellite can be changed in the model very easily.

2.1. Translational dynamics

The translational dynamics of the satellite are written in the inertial frame since the E-Sail is envisioned to operate in deep space. The position vector of the satellite is $\vec{r}_B = [x_B, y_B, z_B]^T$ and the velocity is then $\vec{V}_{B/I} = [\dot{x}, \dot{y}, \dot{z}]$. The acceleration of the satellite is found by summing the total forces on the body and dividing by the mass of the satellite where subscripts are used to denote the different forces from Propulsion (P), and Tether (T).

$$\vec{a}_{B/I} = \frac{1}{m_S}(\vec{F_P} + \vec{F_T}) \tag{1}$$

2.2. Attitude dynamics

The attitude dynamics are formulated assuming the satellite can rotate about three axes through the standard 3-2-1 aerospace sequence using angles ψ,θ, and ϕ to represent the yaw, pitch and roll angles [11]. This can be seen in Fig. 2.

It is well known that the dynamic equations produced by the using three orientation parameters results in a singularity when the pitch angle is equal to 90°. As such, the orientation of the satellite is parameterized using four parameters known as quaternions [12], [13]. The kinematic equations for quaternions are given using the equation below

$$\begin{Bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{Bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \begin{Bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{Bmatrix} \tag{2}$$

where q_i are the four quaternions and p, q, r are the components of the angular velocity vector in the body frame. The rotational dynamics are identical to a standard six degree of freedom model [11]. The skew symmetric operator is denoted by $\mathbf{S}()$. Multiplying this matrix by a vector is equivalent to a cross product.

$$\dot{\vec{\omega}}_{B/I} = I_B^{-1}(\vec{M_P} + \mathbf{S}(\vec{r_S})\vec{F_T} - \mathbf{S}(\vec{\omega}_{B/I})I_B\vec{\omega}_{B/I}) \tag{3}$$

The applied moments use subscripts (P) for propulsion, and (T) for tether. The tether moment is a cross product involving the distance from the center of mass of the satellite to the connection point of tether and the tether force.

2.3. Propulsion model

Each satellite is equipped with N_P thrusters that have a fixed I_{sp}. The mass flow rate of each thruster is given by the equation below where P is the instantaneous force of the thruster.

$$\dot{m}_i = \sigma_i \frac{P}{9.81\ I_{sp}} \tag{4}$$

Each thruster is either on or off as given by the variable σ which is either a 1 or a 0. When the thruster is on, the force applied is equal to P and when the thruster is off the thrust applied is equal to zero. Thus in

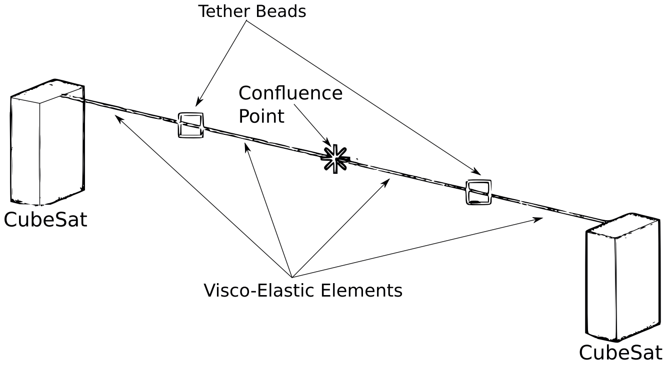

Fig. 1. Example two satellite E-Sail dynamic model components.