Acta Astronautica 131 (2017) 145–151

Contents lists available at ScienceDirect

Acta Astronautica

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

Thrust vectoring of an electric solar wind sail with a realistic sail shape

P. Toivanen*, P. Janhunen

Finnish Meteorological Institute, FIN-00101 Helsinki, Finland

ARTICLE INFO

Keywords:
Electric solar wind sail
Attitude control
Transverse thrust

ABSTRACT

The shape of a rotating electric solar wind sail under the centrifugal force and solar wind dynamic pressure is modeled to address the sail attitude maintenance and thrust vectoring. The sail rig assumes centrifugally stretched main tethers that extend radially outward from the spacecraft in the sail spin plane. Furthermore, the tips of the main tethers host remote units that are connected by auxiliary tethers at the sail rim. Here, we derive the equation of main tether shape and present both a numerical solution and an analytical approximation for the shape as parametrized both by the ratio of the electric sail force to the centrifugal force and the sail orientation with respect to the solar wind direction. The resulting shape is such that near the spacecraft, the roots of the main tethers form a cone, whereas towards the rim, this coning is flattened by the centrifugal force, and the sail is coplanar with the sail spin plane. Our approximation for the sail shape is parametrized only by the tether root coning angle and the main tether length. Using the approximate shape, we obtain the torque and thrust of the electric sail force applied to the sail. As a result, the amplitude of the tether voltage modulation required for the maintenance of the sail attitude is given as a torque-free solution. The amplitude is smaller than that previously obtained for a rigid single tether resembling a spherical pendulum. This implies that less thrusting margin is required for the maintenance of the sail attitude. For a given voltage modulation, the thrust vectoring is then considered in terms of the radial and transverse thrust components.

1. Introduction

The electric solar wind sail is a propulsion system that uses the solar wind proton flow as a source of momentum for spacecraft thrust [1]. The momentum of the solar wind is transferred to the spacecraft by electrically charged light-weight tethers that deflect the proton flow. The sail electrostatic effective area is then much larger than the mechanical area of the tethers, and the system promises high specific acceleration up to about 10 mm/s^2 [2]. As the tethers are polarized at a high positive voltage they attract electrons that in turn tend to neutralize the tether charge state. However, only a modest amount of electric power of a few hundred watts is required to operate electron guns to maintain the sail charge state, and the sail can easily be powered by solar panels [3,4]. The main tethers are centrifugally deployed radially outward from the spacecraft in the sail spin plane (Fig. 1). To be tolerant to the micro-meteoroid flux each tether has a redundant structure that comprises a number (typically 4) of 20–50 μm metal wires bonded to each other, for example by ultrasonic welding [5]. As a baseline design, the tips of the main tethers host remote units that are connected by auxiliary tethers at the sail perimeter to provide mechanical stability to the sail [6].

As the electric sail offers a large effective sail area with modest power consumption and low mass, it promises a propellantless continuous low thrust system for spacecraft propulsion for various kinds of missions [7]. These include fast transit to the heliopause [8], missions in non-Keplerian orbit such as helioseismology in a solar halo orbit [9], space weather monitoring with an extended warning time (closer to the sun than L1), multi-asteroid touring mission. Using the electric sail, such missions can typically be accomplished without planetary gravity assist maneuvers and associated launch windows. If planetary swing-bys are planned during the mission, each solar eclipse has to be carefully considered to avoid drastic thermal contraction and expansion of the sail tethers [10]. In addition to scientific missions, the electric sail can be used for planetary defense as a gravity tractor [11] or an impactor [12] and to rendezvous with such Potentially Hazardous Objects that cannot be reached by conventional propulsion systems [13]. The electric sail has also been suggested as a key method of transportation for products of asteroid mining [14]. Specifically, water from asteroids can be used for in-orbit production of LH2/LOX by electrolysis to provide a cost efficient way of transporting infrastructure associated with manned Mars missions [15].

The electric sail has an intrinsic means for its flight control, i.e., spin plane attitude control, maintenance, and maneuvers. These can be realized by applying differential voltage modulation to the sail tethers

---

* Corresponding author.
E-mail address: petri.toivanen@fmi.fi (P. Toivanen).

http://dx.doi.org/10.1016/j.actaastro.2016.11.027
Received 27 April 2016; Received in revised form 23 September 2016; Accepted 16 November 2016

Nomenclature

a	voltage modulation torque-free
c	cosine function
$\mathbf{e}$	unit vector
$\mathbf{F}$	electric sail force
$\mathcal{F}$	total sail thrust
$\mathbf{G}$	centrifugal force
g	voltage modulation general
$\mathcal{I}$	integral
k	force ratio
L	main tether length
l	coordinate along the main tether
M	total mass
N	number of main tethers
m	single main tether mass
s	sine function
$\mathbf{T}$	main tether tension
$\mathfrak{T}$	electric sail torque
$\mathcal{T}$	total sail torque
u	local tether tangent
$\mathbf{v}$	solar wind velocity
v	solar wind speed
(x, y, z)	Cartesian coordinates
α	sail angle
γ	local tether coning angle
Δt	rotation period
μ	linear mass density
ψ	thrust angle
(ρ, ϕ, z)	circular cylindrical coordinates
$\boldsymbol{\tau}$	angular torque density
ξ	electric sail force factor
ω	sail spin rate

Subscripts

0	tether root
i	index
L	tether length
mt	main tether
q	vector component index
ru	remote unit
s	sail
(x, y, z)	Cartesian coordinates
α	sail angle
γ	local tether coning angle
(ρ, ϕ, z)	circular cylindrical coordinates

Superscripts

j	summation index
*	orbital frame of reference

synchronously with the sail spin [16]. Thus the flight control is similar to the helicopter rotor flight control based on the blades' angle of attack. Furthermore, the sail can fully be turned off for orbital coasting phases or proximity maneuvers near light weight targets such as small asteroids. The coasting phases are also central to optimal transfer orbits between circular, for example, planetary orbits [18] (when reaching a target in an elliptical orbit such as the comet 67P/Churyumov–Gerasimenko coasting phases are not needed [19]). Note that these coasting phases are not associated with the planetary gravity assist maneuvers. Navigation to the target is also feasible, in spite of the variable nature of the solar wind [20].

In this paper, we derive an integral equation for the sail main tether shape under the solar wind dynamical pressure and the centrifugal forces in Section 2.1. The resulting equation of the tether shape is then solved numerically (Section 2.2) and an analytical approximation for the shape is then obtained (Section 2.3). Using this approximation, we obtain general expressions for the thrust (Section 3.1) and the torque (Section 3.2) arising from the solar wind transfer of momentum to the sail. In Section 4.1, we introduce a tether voltage modulation that leads to a torque-free sail motion. Finally, in Section 4.2, we consider the sail thrust vectoring in terms of both the radial and transverse thrust.

The reference frames used in this paper are illustrated in Fig. 1. One of the frames (x^*, y^*, z^*) is the orbital reference frame with the z^*-axis pointing to the sun, the y^*-axis being in the direction of the negative normal of the orbital plane, and the x^* completing the triad in the direction of the orbital velocity vector. In the other system (x, y, z), z is aligned with the sail spin axis, and x is chosen so that the solar wind nominal direction is in the xz plane. These two systems are related by a rotation around y^*-axis by the sail angle α. In the xyz system, the circular cylindrical coordinates (ρ, ϕ, z) are used.

The reference frames introduced above are local in the following sense: they rotate with respect to the distant stars while the sail is orbiting around the sun; however, the sail itself keeps its orientation with respect to the distant stars; and thus the sail spin axis is slowly rotating (360°/yr) in these non-inertial local frames in terms of the Coriolis effect. In order to maintain the sail orientation with respect to the sun, an additional tether voltage modulation has to be introduced. The amplitude of this modulation is, however, much smaller compared to the modulation associated with the inclined sail [16], and the Coriolis effect can be neglected in this work. It is noted, however, that the Coriolis effect can only be partially canceled by the main tether voltage modulation and it leads to a secular variation in the sail spin rate [16]. This is a topic considered in a future study that addresses the electric sail spin rate variations and control using the model developed in this paper.

2. Tether shape

2.1. Equation of tether shape

The electric sail tether shape under the solar wind forcing can be

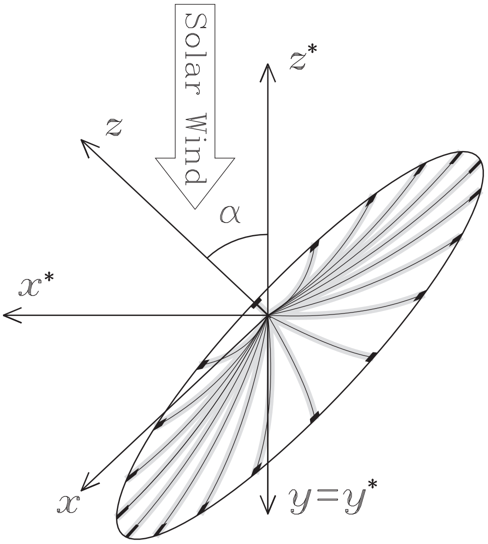

Fig. 1. Electric sail flight configuration and two coordinate systems: (x^*, y^*, z^*) is the orbital frame of reference; and (x, y, z) is rotated around the y^*-axis by the sail angle alpha.