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Electric sail control mode for amplified transverse thrust

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ABSTRACT

The electric solar wind sail produces thrust by centrifugally spanned high voltage tethers interacting with the solar wind protons. The sail attitude can be controlled and attitude maneuvers are possible by tether voltage modulation synchronous with the sail rotation. Especially, the sail can be inclined with respect to the solar wind direction to obtain transverse thrust to change the osculating orbit angular momentum. Such an inclination has to be maintained by a continual control voltage modulation. Consequently, the tether voltage available for the thrust is less than the maximum voltage provided by the power system. Using a spherical pendulum as a model for a single rotating tether, we derive analytical estimations for the control efficiency for two separate sail control modes. One is a continuous control modulation that corresponds to strictly planar tether tip motion. The other is an on–off modulation with the tether tip moving along a closed loop on a saddle surface. The novel on–off mode is introduced here to both amplify the transverse thrust and reduce the power consumption. During the rotation cycle, the maximum voltage is applied to the tether only over two thrusting arcs when most of the transverse thrust is produced. In addition to the transverse thrust, we obtain the thrusting angle and electric power consumption for the two control modes. It is concluded that while the thrusting angle is about half of the sail inclination for the continuous modulation it approximately equals to the inclination angle for the on–off modulation. The efficiency of the on–off mode is emphasized when power consumption is considered, and the on–off mode can be used to improve the propulsive acceleration through the reduced power system mass.

1. Introduction

The thrust of the electric solar wind sail is produced through an interaction of the solar wind protons and electrostatic electric field of long electrically charged tethers [1]. The tethers are spanned centrifugally to form a sail rig slowly rotating together with the spacecraft main body (Fig. 1). The positive tether voltage of a few tens of kilovolts is actively maintained by an electron gun powered by solar panels. The spatial scale size of the electric field structure around the tethers is several hundreds of meters forming an effective sail area against the solar wind dynamic pressure. The obtained thrust is several hundreds of nN/m over the tether length [2]. The tethers are lightweight and made of micrometer thin (a few tens of μm) aluminum wires ultrasonically bonded together [3] for redundancy against the micro-meteoroid flux.

To maintain the tethers rotating in unison, there are two principal electric solar wind sail designs. One assumes mechanically coupled tethers by flexible auxiliary tethers connecting the main tether tips [4]. At each tether tip, there is a remote unit that includes auxiliary tether reels for the sail deployment while the main tethers are reeled out from the central body of the spacecraft. As a baseline, miniature cold gas thrusters are also included to start the sail rotation by producing the required angular momentum [5].

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Nomenclature

A, B	thrusting arcs
$\mathbf{a}$	acceleration
a	power series coefficients
$\mathbf{e}$	unit vector
F	force
g	tether voltage modulation $\in [0, 1]$
I	integral
k	force parameter
l	tether length
m	mass
p	thrusting arc factor
(r, θ, ϕ)	spherical polar coordinates
$\mathbf{u}$	solar wind velocity
V	tether voltage
(X, Y, Z)	Cartesian coordinates
α	sail angle
κ	force parameter scaled to angular frequency
Λ	sail coning angle
μ	free plane tilt angle
ν	angular frequency
ρ	electric sail to centrifugal force ratio
χ	$\tan \alpha \tan \Lambda$
ξ	electric sail thrust factor
ω	angular velocity
$< >$	angular average
$< >_t$	temporal average

Subscripts

A, B	thrusting arcs
a	angular average
CF	centrifugal
ES	electric solar wind sail
(r, θ, ϕ)	spherical polar coordinates
(x, y, z)	Cartesian coordinates
Θ	thrusting arc index
0	reference initial value
$\perp$	perpendicular (radial)
$\parallel$	parallel (transverse)
$*$	orbital coordinates

Superscripts

Θ	thrusting arc index

The other design assumes that the tethers are mechanically uncoupled and the rotation rate is controlled by freely guided photonic blades at each tether tip [6].

The electric solar wind sail attitude maintenance and maneuvers can be introduced by modulating the voltage of each tether individually and synchronously with the spacecraft rotation. The sail nominal rotation plane can be turned to incline the sail thrust vector relative to the Sun-spacecraft direction. In the normal flying mode, the sail is inclined with respect to the Sun-spacecraft direction either to gather or diminish the osculating orbit angular momentum. In this mode, tether voltages have to be modulated continually. As the average tether voltage is less than the maximum provided by the spacecraft power system, the control mode affects the sail efficiency.

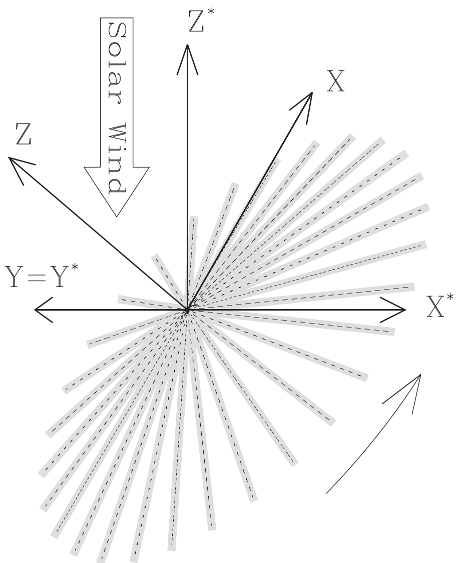

Fig. 1. Slowly rotating electric solar wind sail with an electrostatic effective sail area (gray shading) around the thin tethers (dashed lines).

The electric solar wind sail thrusting geometry is such that the thrust generated by a single tether is along the solar wind component perpendicular to the tether (Fig. 2). For simplicity, the coordinate systems in this study are as follows. The spacecraft orbital coordinates are such that X^* is along the spacecraft orbital velocity, Z^* points to the Sun, and Y^* is normal to the orbital plane. The sail coordinates (X, Y, Z) are then rotated by the sail angle (α) around the Y^*-axis as shown in Fig. 2. The thrust magnitude and direction depend then on the tether rotation phase as depicted in Fig. 2 in terms of the tether acceleration ($\mathbf{a}$). When the tether (white circle) is normal to the orbital plane ($X-Z$ plane) the thrust has only a radial component ($\mathbf{a}_\perp$).

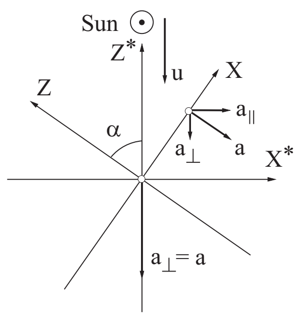

Fig. 2. Geometry and rotation phase dependence of the thrust orientation in the sail coordinates (X, Z) and orbital coordinates (X^*, Z^*).