

An Intrinsic Way to Control E-Sail Spin

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June 27, 2014

Abstract

We show that by having the auxtethers made partly or completely of conducting material and by controlling their voltages, it is possible to control the spin rate of the electric solar wind sail by using the electric sail effect itself. The proposed intrinsic spin rate control scheme has enough control authority to overcome the secular change of the spin rate due to orbital Coriolis effect.

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Nomenclature

f	=	E-sail thrust per unit tether length
f_0	=	f at $r = r_0$
\mathbf{F}	=	E-sail force acting on tether
\mathbf{F}_s	=	Component of \mathbf{F} along spin plane
\mathbf{F}_n	=	Component of \mathbf{F} perpendicular to spin plane
g	=	Factor by which maintether voltage is changed when aux tether segment is electrified
k	=	Factor by which centrifugal tension exceeds E-sail force
l_{aux}	=	Length of aux tether segment
m	=	Lumped mass of one tether subsystem (maintether, RemoteUnit and aux tether)
N	=	Number of tethers in the E-sail
r	=	Solar distance
r_0	=	Base solar distance, 1 au
R	=	Tether length
t	=	Time
x	=	Cartesian coordinate along thrust vector component perpendicular to solar wind
y	=	Cartesian coordinate perpendicular to x and z so that XYZ forms a right-handed system
z	=	Cartesian coordinate along solar wind direction
X, Y, Z	=	Coordinate axes corresponding to coordinates x, y, z
α	=	Angle between antisolarwind direction and E-sail spin axis
$\delta\varphi$	=	Length of phase angle interval in which aux tether segment is electrified
τ_c	=	Coriolis torque acting on one tether subsystem
$\Delta\tau$	=	Instantaneous spin-changing torque generated by electrified aux tether segment
τ_{ave}	=	Time average of $\Delta\tau$
$\boldsymbol{\omega}$	=	E-sail spin angular frequency vector
Ω	=	Orbital angular frequency
Ω_0	=	Orbital angular frequency at $r = r_0$

1 Introduction

The electric solar wind sail (E-sail) uses charged tethers to tap momentum from the solar wind (SW) [1]. The baseline configuration uses a set of radial main tethers which are kept under centrifugal tension by spinning the system [2]. For dynamical stability, the tips of the main tethers are connected together by auxiliary tethers [2]. For each tether, the generated E-sail thrust points along the tether-perpendicular component of the SW flow direction. Thrust vectoring is thereby possible by inclining the sail (the tether spin plane) with respect to the SW flow (Fig. 1). For each tether, the magnitude of the thrust can be controlled by modulating the voltage of the tether, and sail attitude maneuvers are possible by E-sail force only.

If the E-sail spacecraft orbits the Sun while having its sail inclined, the orbital Coriolis acceleration interacts in a nontrivial way with the spin of the tether rig [3]. Specifically, the spin rate accelerates (decelerates) if the sail is inclined so as to spiral the orbit outwards (inwards) in the solar system. The angular acceleration of the rotating sail is approximately given by

$$\frac{d\omega(t)}{dt} = (\Omega \tan \alpha) \omega(t) \quad (1)$$

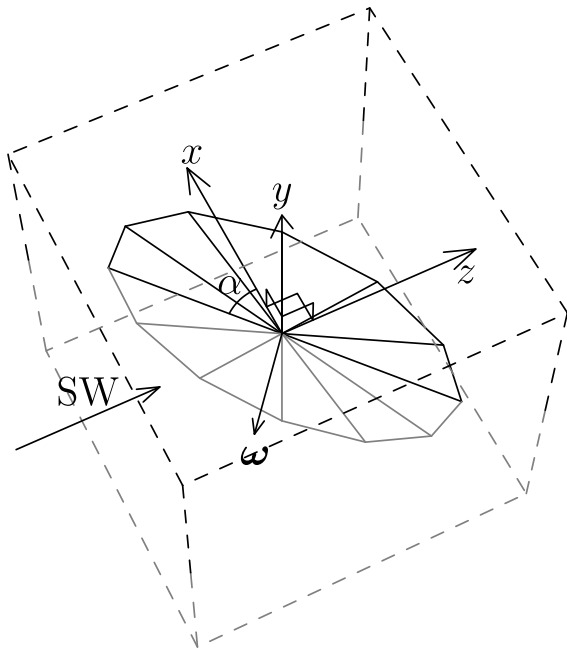


Figure 1: Spinning E-sail inclined at angle α with respect to solar wind (SW) flow (α lies in the XZ plane). Domain $y < 0$ is drawn in grayscale to help visualization.

where the sail inclination angle α is taken to be positive if the sail accelerates away from the sun (i.e. if the E-sail thrust component along the orbital velocity vector is positive). Equation 1 leads to exponential change of ω unless compensated by spin rate control.

The E-sail also needs spin rate control to generate angular momentum during deployment of the tethers. Cold gas thrusters and ionic liquid field effect electric propulsion (FEEP) thrusters have been prototyped for spin rate control yielding RemoteUnit mass of 0.56 kg [4], and solar photonic blades have been considered at lower technical readiness level (TRL) [5]. Here we propose a new intrinsic method of controlling the spin rate by the E-sail force itself.

2 Spin rate modulation by electrified auxetethers

Consider an E-sail as in Fig. 1 where now the auxiliary tethers (auxtethers) can at least partly be put under voltage. A segment of auxtether generates E-sail thrust which is perpendicular to it if one neglects end effects. We now want to show that if the auxtether voltage can be controlled independently from the adjacent maintether voltage, pure E-sail spin rate control becomes possible.

Figure 2a shows an E-sail inclined at angle α to the SW flow and one of its charged maintethers which at the moment happens to lie in the XZ plane i.e. in the plane of the figure. At this moment the maintether in question generates thrust vector \mathbf{F} which is perpendicular to the tether spinplane (dashed line), i.e. inclined by angle α with respect to the SW.

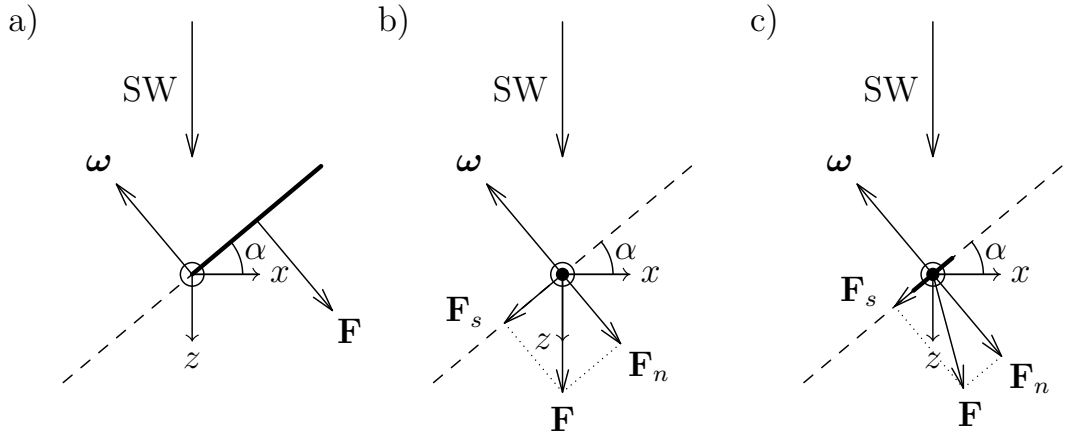


Figure 2: (a) Considering a single tether (thick line) lying momentarily in the XZ plane and viewed along Y . E-sail force \mathbf{F} is along the tether-perpendicular component of the SW. (b) When tether is parallel to Y , it is already perpendicular to SW and \mathbf{F} is aligned with SW. \mathbf{F} is decomposed to spinplane aligned component \mathbf{F}_s and spinplane perpendicular component \mathbf{F}_n . (c) Tether parallel to Y and with adjacent electrified auxetether segment. Spinplane E-sail force component \mathbf{F}_s is smaller than in (b).

Figure 2b shows the same maintether a quarter cycle later when it is aligned along Y axis. Now the maintether is already perpendicular to the SW so that the thrust \mathbf{F} is simply aligned with the SW. \mathbf{F} can be decomposed into spinplane component \mathbf{F}_s and spinplane normal component \mathbf{F}_n . The spinplane component of the E-sail thrust tends to decrease the tether's ω when it climbs upstream. The reverse happens half a cycle later when the tether moves downstream so that overall no change in spin rate is generated.

In Fig. 2c there is a short charged auxetether segment attached to the tip of the maintether at the same moment as in 2b. The E-sail thrust vector \mathbf{F} is now a vector sum of the maintether thrust and the auxetether thrust. The maintether thrust is along the SW flow as in 2b, but the auxetether thrust is perpendicular to the auxetether, i.e. perpendicular to the spin plane. As a result, \mathbf{F} is not fully aligned with the SW and its spinplane component F_s is smaller. To prevent the sail from turning, it is necessary that F_n has the same value when the tether is moving upstream and downstream. However, the spinplane component F_s can be different because the same F_n can be obtained by different combinations of the maintether and auxetether voltages. Effectively, we have two control parameters (maintether voltage and auxetether voltage) which allows us to control the two thrust parameters F_s and F_n freely. By having the same F_n but different F_s in the upstream and downstream portions of the maintether's cycle, one can modify the sail's spin rate while keeping its orientation fixed.

3 Effect strength

Consider an E-sail consisting of N maintethers of length R , approximating each by a point mass m located at the tip so that m contains the masses of the

maintether, the Remote Unit and the associated aux tether segment. Assume that the E-sail thrust per unit length f at solar distance r_0 (select $r_0 = 1$ au for definiteness) is f_0 . At other distances r , $f = f_0(r_0/r)$ [2]. Assume also that at each solar distance r the spin rate ω is chosen such that the centrifugal tension of the maintether is k times the E-sail force acting on it where one typically requires $k \gtrsim 5$ for stability. This implies $mR\omega^2 = kfR$ so that

$$\omega = \sqrt{\frac{kf}{m}} = \sqrt{\frac{kf_0r_0}{mr}}. \quad (2)$$

Equation (1) gives the secular angular acceleration due to the orbital Coriolis effect. The corresponding Coriolis torque is

$$\tau_c = mR^2 \frac{d\omega}{dt} = mR^2 \Omega \omega \tan \alpha. \quad (3)$$

Thus, Eq. (3) gives the torque that must be compensated by the electrified aux tether E-sail effect.

Consider the tether when it's pointed along Y (Fig. 2b,c) where the length of its associated aux tether segment is $l_{\text{aux}} = 2\pi R/N$. If the maintether has voltage and the aux tether has not, the E-sail thrust acting on the maintether is $F = fR$ whose components are $F_s = F \sin \alpha$ and $F_n = F \cos \alpha$. If both tethers have voltage, then $F_s = gfR \sin \alpha$ and $F_n = gfR \cos \alpha + fl_{\text{aux}}$ where g is a dimensionless factor by which the maintether voltage is modulated ($0 \leq g \leq 1$). Requiring that F_n causes the same torque in both cases implies

$$1 - g = \frac{2l_{\text{aux}}}{R \cos \alpha} \quad (4)$$

and the difference in spin axis aligned torques becomes

$$\Delta\tau = fl_{\text{aux}}R \tan \alpha = \frac{2\pi}{N} fR^2 \tan \alpha. \quad (5)$$

Let us assume that the aux tether voltage is used only when the tether is close to vertical, in phase angle interval of length $\delta\varphi$, so that the average E-sail torque due to aux tether electrification is $\tau_{\text{ave}} = (\delta\varphi/(2\pi))\Delta\tau$. Requiring $\tau_{\text{ave}} = \tau_c$ we can solve for $\delta\varphi$. Using above definitions, the result can be expressed as

$$\delta\varphi = Nk \frac{\Omega}{\omega} = N\sqrt{k} \left(\frac{r_0}{r}\right) \Omega_0 \sqrt{\frac{m}{f_0}} \quad (6)$$

where Ω_0 is the orbital angular frequency at $r = r_0$: $\Omega = \Omega_0(r_0/r)^{3/2}$. For example for the baseline 1 N E-sail orbiting at 1 au $N = 100$, $k = 5$, $r = r_0$, $\Omega_0 = 2\pi/\text{year} = 2.0 \cdot 10^{-7} \text{ s}^{-1}$, $m = 1 \text{ kg}$, and $f_0 = 500 \text{ nN/m}$ so that $\delta\varphi = 3.6^\circ$. This is a conveniently small fraction of the full circle, hence there is typically an abundant performance margin that can be used e.g. for running the aux tethers at reduced voltage or for having only part of the aux tether being conductive.

4 Conclusion

In many missions the orbital Coriolis effect causes a secular variation of the E-sail spin rate which must be compensated by technical means. We showed

conceptually that this can be effected by making the auxetethers partly or completely from conducting material and having a way to control their voltages. The resulting pure E-sail concept does not need any auxiliary propulsion systems such as cold gas thrusters, FEEP thrusters or photonic blades for its long-term spin rate management.

In the future, more refined engineering studies should be carried out concerning conducting auxetether designs and the voltage regulation mechanisms of the auxetethers. One should also study the details of how the proposed scheme can be used for angular momentum generation during tether deployment.

Acknowledgments

The work was funded by the Academy of Finland grant 250591.

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