Electric Solar Wind Sail: Deployment, Long-Term Dynamics, and Control Hardware Requirements

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The deployment, dynamics, and control of the electric solar wind sail is addressed in terms of the single tether motion. Based on a simple model of a rotating rigid tether as a spherical pendulum, estimates for the goodness of the control system are shown for strictly planar tether tip orbits. It is concluded that the control system is rather inefficient for a slowly rotating sail with a large tether coning angle. The results are conservative as they do not take into account the actual shape of the tether. The long and short-term effects on the sail rotation rate arising from the single tether dynamics are addressed. We also present preliminary results on a new control scheme assuming non-planar tether tip orbits. It is argued that the scheme will improve the electric sail control system efficiency.

Nomenclature

(*Nomenclature entries should have the units identified*)

r, Θ, φ	=	spherical coordinates
X,Y,Z	=	cartesian coordinates
α	=	sail angle
φ_0	=	solar zenith angle
λ	=	electric sail force constant
l	=	tether length
t	=	time
ω	=	tether rotation rate
Λ	=	tether coning angle
g	=	tether voltage modulation
X	=	tan(α)tan(Λ)
ρ	=	electric force ratio to the centrifugal force
Ω	=	Earth orbital angular velocity
Ψ	=	tether rotation plane tilt angle

Introduction

Electric sail space propulsion system is an electro-mechanical system with strawman components of conducting lightweight micro-meteoroid tolerant tethers, electron guns, and solar panels [1,2]. The tethers are charged to a positive high voltage of a few tens of kV to deviate the solar wind proton flow to obtain the wind momentum as spacecraft thrust. The thrust has been estimated to be several hundreds of nN per tether unit length based on particle-in-cell plasma simulations [2] and analytical analysis [3]. The positive tethers collect electrons and the positive charge state is maintained by the electron gun. The resulting electron current loop connects the tethers, electron gun, and solar wind plasma and using only a moderate amount of solar panel power.

Presently, there are two principal designs of the electric sail (Fig. 1). One is such that the tether tips are mechanically connected with perforated auxiliary tether. Each of the tips are equipped with a remote unit that includes the auxiliary tether reels and cold gas or FEEP thrusters. The remote unit with a mass about 500 grams was manufactured and space quality tested under the ESAIL project of EU/FP7 program. As the electric sail is deployed from a spinning spacecraft by unreeling the long tethers, the remote unit thrust sources have to be added to obtain the required angular momentum of the fully opened sail. Recently, it was suggested that relatively small solar blades can be attached to the tether tips for the deployment thrust and flight time control of the tether rotation rates individually [4]. The other sail design is then such that the tether tips are mechanically free and the flight time control of the tether rotation rates is done individually by using Freely Guided Photonic Blades (FGPB).

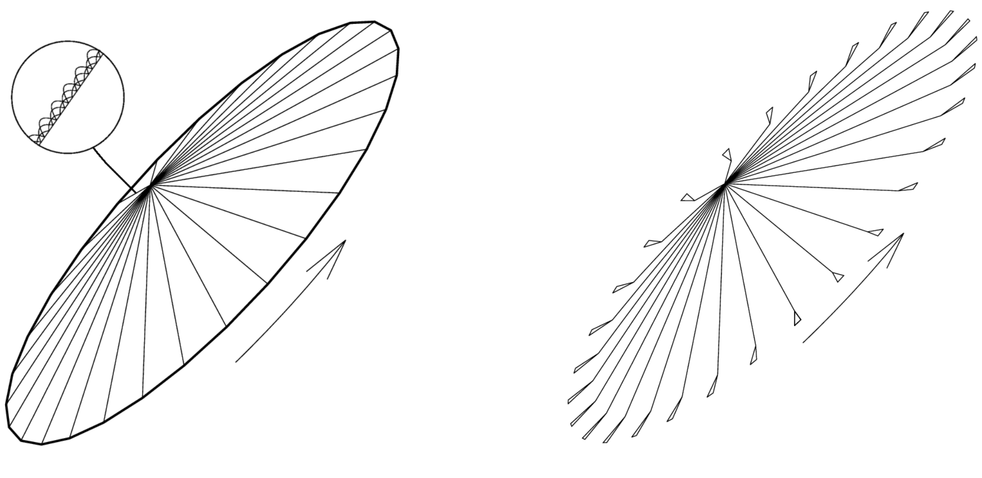

Fig. 1 Electric sail designs use either auxiliary tethers and remote units (left) or Freely Guided Photonic Blades (right) for the sail flight time stability.

The electric sail control algorithms depend on the sail design. Most notably, for the design with the mechanically connected tether tips, the tethers rotate in unison whereas for the case of free tethers, the tether rotation rate is typically a function of the rotation phase [5]. In this paper, we consider the controlled planar motion of free tethers. We address this control scheme in terms of both the sail power system mass efficiency and the ratio of the radial and azimuthal thrust components directed perpendicular and parallel to the sail orbital motion. It is shown that the control routine becomes inefficient for large coning angles corresponding to slow sail rotation rates. Motivated by these findings, we suggest a new control scheme that does not assume strict planar motion. Our preliminary numerical calculation indicates that the suggested types of tether tip orbit exist, and the control scheme based on these orbits seems to improve the control system efficiency.

Tether Planar Orbit Control Efficiency

Assuming the tether being a thin rigid beam, the rotational dynamics of the tether can be described by a spherical pendulum. The equation of motion is written spherical coordinates as

$$\begin{aligned} \ddot{\theta} - \sin\theta\cos\theta\,\dot{\phi}^2 &= \frac{\lambda}{l} g\left(\sin\alpha\cos\theta\cos(\phi-\phi_0) - \cos\alpha\sin\theta\right) \\ \frac{d}{dt}\left(\sin^2\theta\dot{\phi}\right) &= -\frac{\lambda}{l} g\sin\alpha\sin\theta\sin\phi, \end{aligned} \tag{1}$$

where α and φ are the sail inclination angle and the sun azimuth angle [5]. The tether motion is considered in the SE (Solar Ecliptic) coordinate system shown in Fig. 1. In this system, the apparent controlled tether motion is planar with a constant coning angle ($\Lambda = \Theta - \pi/2$). It can be shown that for a voltage modulation of

$$g(\phi) = \frac{(1-\chi)^3}{(1+\chi\cos\phi)^3} \tag{2}$$

the solution with ($d\Theta/dt$ = 0) exist for any given realistic sail angle (X = $tan(\alpha)tan(\Lambda)$).

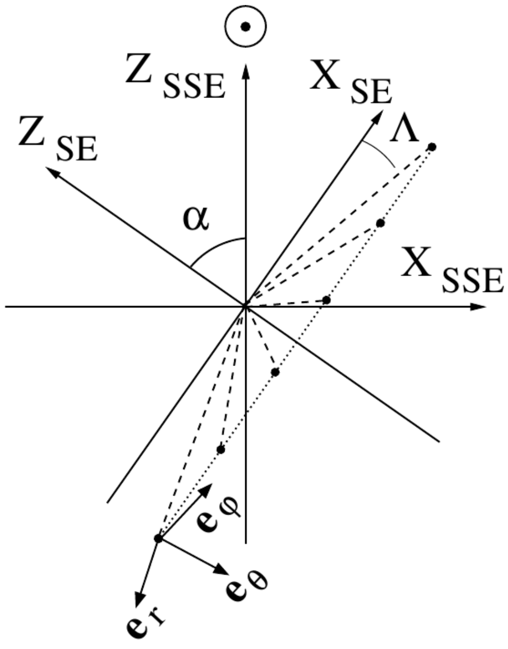

Fig. 2 Two coordinate systems of SE (Sail Eccliptic) and (Sail-centric Solar Ecliptic).

The tether motion can be parametrized by the ratio (ρ) of the electric sail and centrifugal forces. Fig. 3a shows the sail coning angle as a contour plot with the equicontour values in degrees. As expected the coning angle increases for decreasing sail rotation rate (increasing ρ), but it depends also strongly on the sail inclination angle. Another central feature of this control modulation is that the tether rotation rate shows considerable dependence on the rotation phase when the sail is inclined (Fig. 3b).

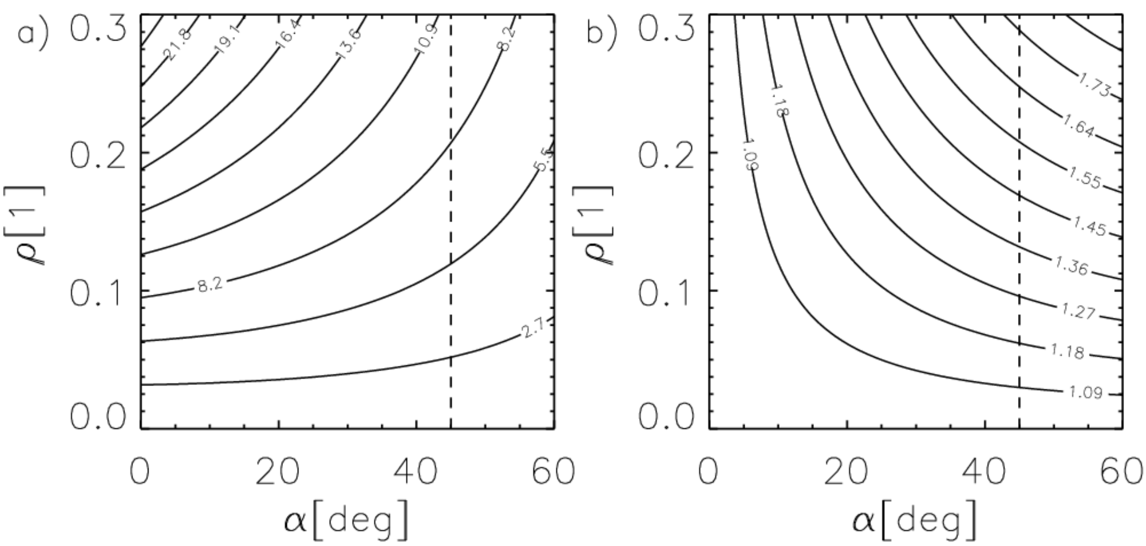

Fig. 3 Equicontours of the coning angle (a) and the amplitude ratio of the tether rotation rate (b).

Figure 4 shows the thrust integrated over the tether rotation phase. The azimuthal component aligned with the sail orbital motion along the X_{SSE} axis (Fig. 4a) has its maximum at ρ = 0 and α = 45 deg. For larger rho values, the azimuthal thrust decreases clearly and the maximum is reached with sail angles below 45 deg. For example, when ρ equals to about 0.2, the maximum is at around α equals to 40 deg. Note that the same level of azimuthal thrust is gained with smaller sail inclination with a sail spinning faster. The radial component aligned with the Z_{SSE} axis (Fig. 4b) decreases with the decreasing sail spin rate and increasing sail inclination as expected.

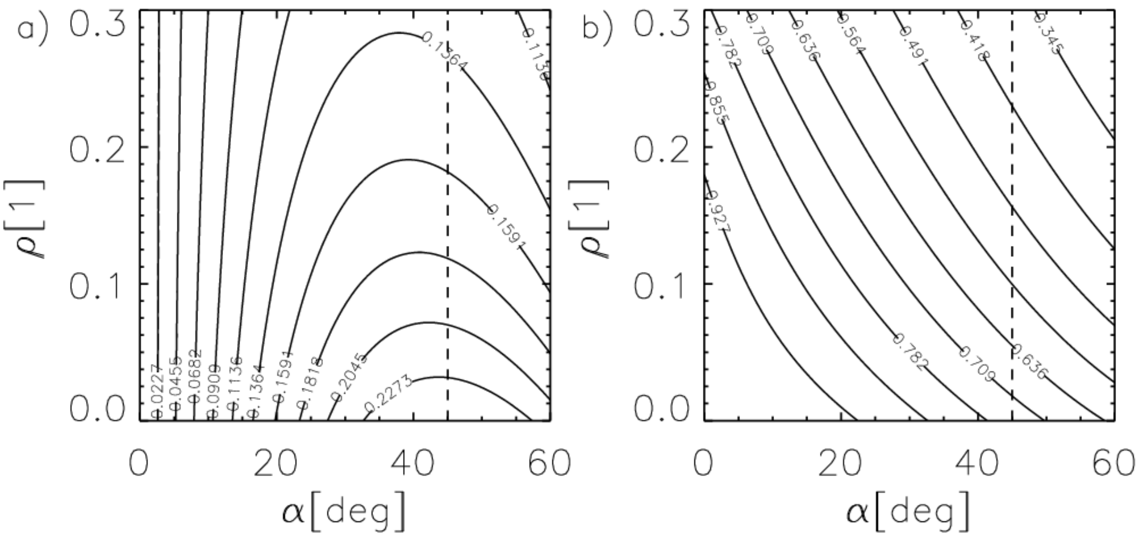

Fig. 4 Equicontours of the total thrust in azimuthal and radial directions. The contour levels are scaled to maximum at (ρ = α = 0).

The inefficieny of the sail control for slowly rotating sails (large ρ) is also apparent when the mass of the power system running the sail current system is considered. The power system mass scales as $V^{3/2}$ to the maximum voltage V of the power system design [6]. Hence the tether voltage averaged over the tether rotation gives the power system mass efficiency implied the applied control scheme (Fig. 5). It can be seen that the effciency is significantly reduced as a function of ρ.

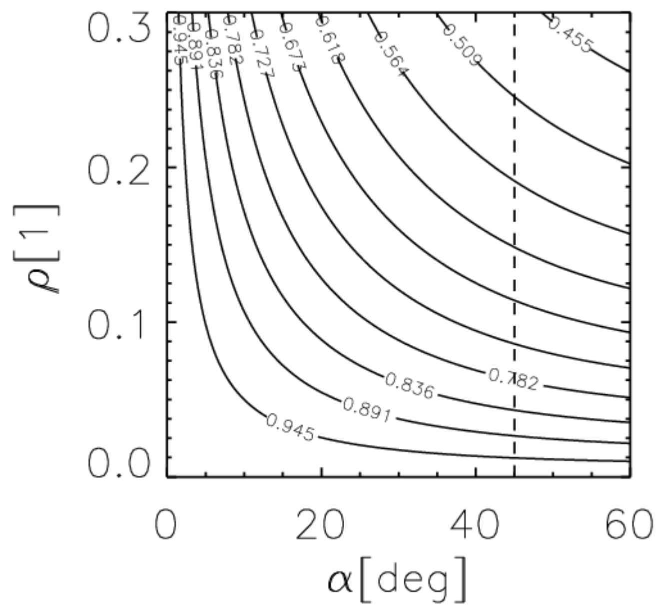

Fig. 5 Equicontours of the power system mass efficiency propotional to the averaged modulation voltage over the maximum voltage to the power of 3/2.

Ultimately the inefficiency of the control scheme arises from the fact that the electric sail force is directed along the solar wind component perpendicular to the tether. Thus depending on the tether rotation phase the instantaneous thrust has a significant azimuthal component only when it is in the sectors near the X_{SSE} axis. In sectors around the Y_{SSE} axis, the instantaneous thrust is mostly radial. Furthermore, maintaining the tether planar motion requires large voltage modulation amplitude relative to the maximum tether voltage. This leads to large variations of the tether angular speed as a function of the rotation phase. Thus a considerable amount of the available thrust is lost by this control scheme for slowly rotating sails. This can be avoided by increasing the sail spin rate in the limits of the tether material tensile strength. Note that these conclusions are strictly based on the assumption the tether being a rigid beam and on the adopted control scheme. These topics are further addressed below. However, the simple model is adequate to get insight into the short and long-term evolution of the sail key parameters, the coning angle and spin rate.

Sail Spin Rate Evolution

There are several factors that affect the single tether or collectively the sail spin rate. These can be attributed to the mechanics of the rotating tethers, solar wind variations, and celestial mechanics [Toivanen2013, Toivanen2012].

Tether Deployment

During the tether deployment, the tether rotation slows down while reeled out. This mundane effect arises from the conservation of the angular momentum, and the rotation rate scales as $1/l^3$ to the tether length l. Although the tethers are lightweight, any realistic initial spin of the spacecraft is far from being adequate for the deployment of a full-scale electric sail and already from this perspective the tether deployment is untrivial. To reduce the required delta-v for the sail deployment the additional thrust is applied to the tether tips either by remote units or FGPB depending on the sail design.

Sail Turning

The electric sail pointing with respect to the sun direction can be controlled with the tether voltage modulation. As the sail is turned, the modulated thrust that turns the tether spin plane also has a component along the tether angular speed enhancing the sail spin rate. Based on the results of reviewed above, the spin rate is proportional to $1/\cos(\alpha)$ (Ref. [5]). If the initial deployment is realized with the sail point to the sun, turning the sail to the flight inclination, increases the spin rate by a factor of about 1.4, an effect that can be used to reduce the amount of propellant of the remote units reserved for the sail deployment.

Solar wind Variation

The solar wind has non-radial components significant in terms of the individual tether rotation. These components induces drift in the tether rotation phase leading ultimately to tether collisions and collapse of the sail in matter of days. As the angular speed of the tether depends on the inclination of its spin plane, it can be controlled by inclining the tether spin planes individually according. Each tether tip is then kept in cone around the nominal phase. This way the solar wind variations can be tolerated and the time scale to the tether collisions can be extended [7]. However, additional thrust by FGPB are required. For the sail design using the auxiliary tethers the solar wind variations play no role.

Coriolis Effect

With a low thrust system, the spacecraft orbits are typically spirals around the sun. When orbiting around the sun, the sail spin plane conserves the orientation to the distant stars as depicted in Figure 6, the SSE coordinate system is not inertial, and the sail appears to be slowly rotating in the SSE system. This corresponds to a small Coriolis force affecting the sail in the SSE system (the term is not included in (1), see Ref. [5]). Thus this force has to be controlled by an additional modulation embedded in the voltage modulation (2) in order to maintain a sail inclination constant with respect to the sun direction. Such an additional modulation induces also a thrust component along the tether rotation accumulating slowly in the sail rotation rate. The sail rotation rate is slowed down when spiraling inward and enhanced when spiraling outward. The temporal change in the rotation rate (ω)is expressed as

$$\omega = \omega_0 e^{\Omega \tan \alpha (t - t_0)} \qquad (3)$$

where Ω is rotation rate of the SSE around the sun. This effect has to be taken into account in mission analysis when designing the additional thrust source both in terms of the auxiliary tether remote units and FGPB.

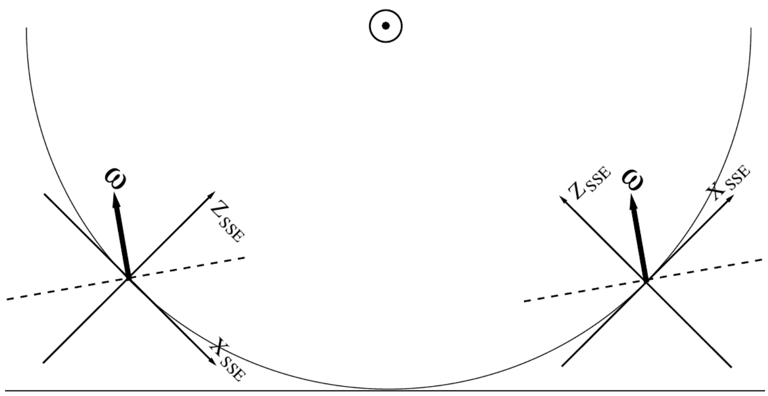

Fig. 6 Slow rotation of the sail in the non-inertial SSE coordinate system while orbiting around the sun.

Non-Planar Tether Orbit Control

As concluded above, the apparent control scheme that maintains the sail tether tips rotating in a plane with a constant coning angle is inefficient in many respects, and there is a need for more efficient control schemes. Here, we sketch an alternative orbit for the tether tip and show that such an orbit exist based on preliminary numerical analysis. Figure 7 shows the proposed orbit of the tether tip (thick solid line) in the SE coordinates. If the tether voltage is turned off, the tether rotates freely on any given plane. Two such planes tilted by some angle

(Ψ) around the X_{SE} axis are considered as shown in Fig. 7. When approaching the rotation phase sector near the X_{SE} axis, the tether voltage is turned on and kept constant at maximum. The voltage is turned off when the tether reaches the plane of free motion with the opposite tilt. The preliminary numerical integration of the equation of motion suggests that orbits of the proposed type exist as shown in Fig. 8. The sail inclination angle is 45 deg.

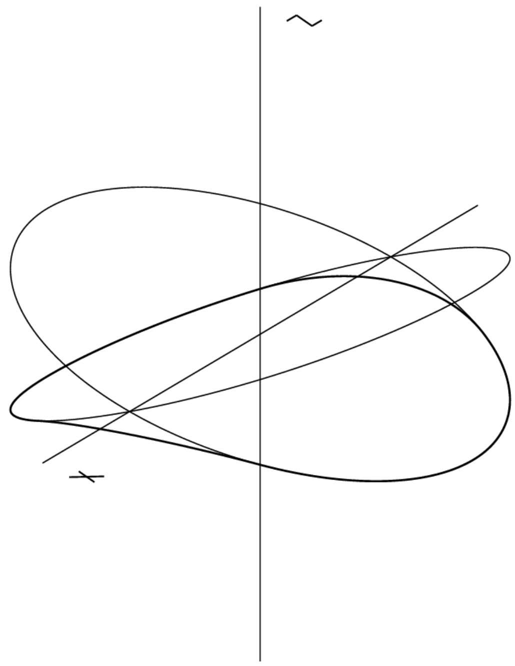

Fig. 7 Alternative orbit of the tether tip for a control scheme with an enhanced efficiency.

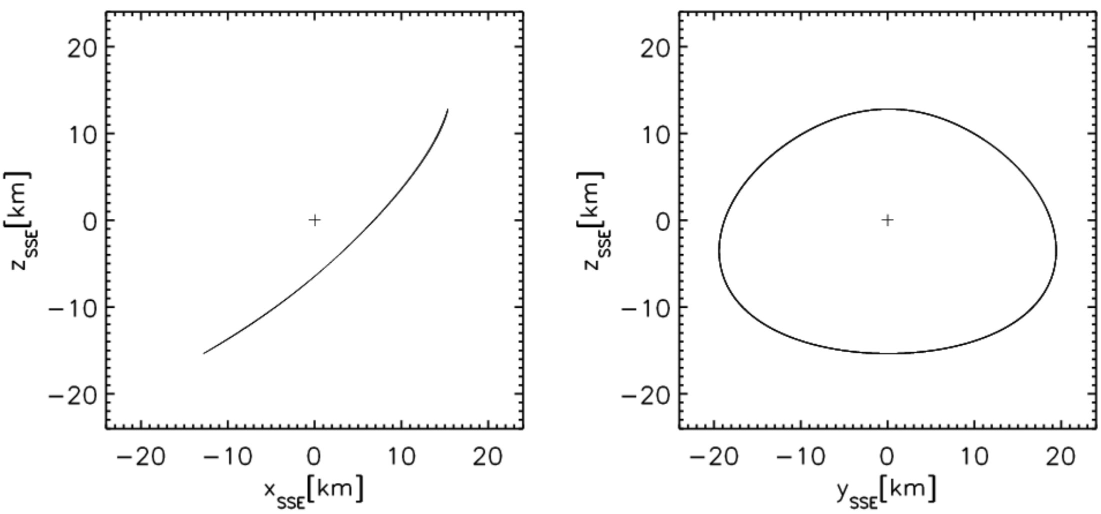

Fig. 8 Numerical solution for the orbit of the tether tip.

There are several promising aspects in the proposed orbit type, and improvement to the tether control efficiency can be expected. The voltage is used at or near the maximum (Fig. 9). The tether rotation rate varies less over the rotation phase (Fig. 9; during the free motion, the rate is constant). The voltage is turned on when the tether is producing azimuthal thrust. When the voltage is on the tether is located near the plane of Z_{SE} equals to zero implying a small coning angle and reduced power consumption and power system mass.

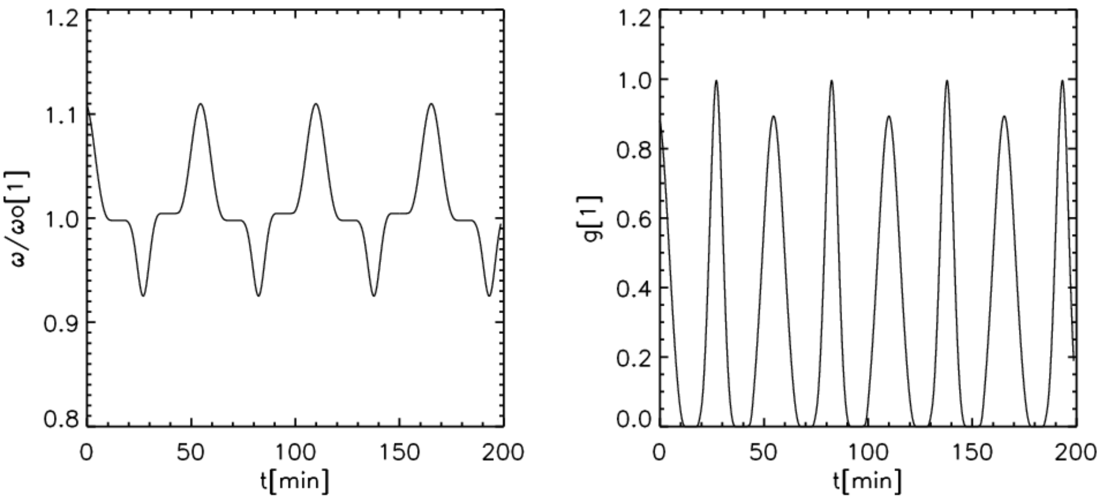

Fig. 9 Relative angular frequency of the tether rotation (left) and voltage modulation (right).

Conclusions and Discussion

The results of this paper concerns the electric sail design with mechanically free tethers. Such design is realized by using the Freely Guided Photonic Blades [4]. Based on our previous analysis on the controlled motion of a free tether [5], we addressed the efficiency of this control scheme that assumes strictly planar tether tip motion. The total thrust integrated over the tether rotation rate shows that this scheme is rather inefficient in producing significant azimuthal thrust component along the sail orbital motion. It also implies low power system mass efficiency for slowly rotating sails with large coning angle.

We also sketched a tether tip orbit alternative to the strictly planar motion. The control scheme based on such orbits seems to be more efficient than that based on the strictly planar orbits. The tether voltage is turn to its maximum in sectors where the tether produces most of the azimuthal thrust while the rest of the rotation phase the voltage is zero and the tether undergoes free motion. The estimates for the efficiency is a topic of a future study.

The results assume a rigid thin beam to model the tether. While the model allows us to identify several effects affecting the sail rotation rate, the estimates on the control system efficiency presented in this paper are rather conservative. The actual shape of the tether rotating under the influence of the solar wind flow is such that the tether coning angle decreases towards the tip of the tether, and for a considerable portion of the tether, the coning angle approaches to zero. While this is a matter of further study, it can be expected that there is an effective coning angle that is smaller than that derived under the rigid tether assumption, and the control system efficiency is underestimated for a slowly rotating sail (the sail rotation rate is a free parameter only to the limit of the tether material tensile strength). Furthermore, similar analysis for the sail designs based on auxiliary tethers are also left for a future study.

Acknowledgments

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