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Heliocentric phasing performance of electric sail spacecraft

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ABSTRACT

We investigate the heliocentric in-orbit repositioning problem of a spacecraft propelled by an Electric Solar Wind Sail. Given an initial circular parking orbit, we look for the heliocentric trajectory that minimizes the time required for the spacecraft to change its azimuthal position, along the initial orbit, of a (prescribed) phasing angle. The in-orbit repositioning problem can be solved using either a drift ahead or a drift behind maneuver and, in general, the flight times for the two cases are different for a given value of the phasing angle. However, there exists a critical azimuthal position, whose value is numerically found, which univocally establishes whether a drift ahead or behind trajectory is superior in terms of flight time it requires for the maneuver to be completed. We solve the optimization problem using an indirect approach for different values of both the spacecraft maximum propulsive acceleration and the phasing angle, and the solution is then specialized to a repositioning problem along the Earth's heliocentric orbit. Finally, we use the simulation results to obtain a first order estimate of the minimum flight times for a scientific mission towards triangular Lagrangian points of the Sun − [Earth + Moon] system.

1. Introduction

The so-called phasing maneuver (or in-orbit repositioning) for a circular orbit is a classical problem of spaceflight mechanics [1,2]. It is known that such a maneuver consists in varying the angular position of a spacecraft that initially tracks a circular orbit of given radius around a celestial body. The phasing maneuver is usually studied by assuming the application of two or more impulses [1,2], and the problem is to find the total velocity variation as a function of the required angular displacement (i.e., the phasing angle) and the total flight time. Such a maneuver often requires a significant velocity variation and a corresponding substantial amount of propellant, especially when using a chemical propulsion system.

To reduce the propellant consumption, a feasible solution is to use a propulsion system with a continuous thrust and a high specific impulse, such as a classical solar electric thruster, or even a more exotic alternative, such as a propellantless propulsion system. In the latter case the existing literature [3–5] already offers interesting examples in which a photonic solar sail is assumed to perform a heliocentric phasing maneuver. Within this context, the aim of this work is to study the performance of a heliocentric phasing maneuver for a spacecraft whose propulsion system is constituted by an Electric Solar Wind Sail (E-sail). The E-sail is an innovative form of spacecraft propulsion system that exploits solar wind plasma momentum by repelling positive ions by means of a number of long tethers, which are biased to a high positive voltage [6], see Fig. 1.

Using an optimal approach, it is possible to find a numerical relationship between the phasing angle, the minimum (optimal) flight time and the spacecraft characteristic acceleration, i.e. the maximum propulsive acceleration of the spacecraft at a distance from the Sun equal to one astronomical unit. In particular, this paper analyzes the performance of an E-sail-based spacecraft for a mission scenario in which the circular parking orbit approximates the Earth's heliocentric orbit, thus extending the previous results of Refs. [3–5] that involve a photonic solar sail-based spacecraft.

The simulation results can also be used to obtain a reasonable approximation of the flight time required to transfer a spacecraft toward Lagrange's triangular points within the Sun − [Earth + Moon] system. Accordingly, the analysis extends the results discussed in Ref. [7] (where a single value of characteristic acceleration is considered) and provides a parametric study of the E-sail performance for this significant mission scenario. Indeed a mission to Lagrange's triangular points would allow a nearby analysis (possibly using multiple flybys) of prospective Earth trojan asteroids to be found (hopefully) in a near future. Currently, the only known celestial body within this special family is the 2010 TK7 asteroid [8], which is in the proximity of Lagrange's point L_4. This asteroid is however difficult to reach with a rendezvous mission

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Nomenclature

a	maximum propulsive acceleration $(\mathrm{mm/s^2})$
a_c	spacecraft characteristic acceleration $(\mathrm{mm/s^2})$
$\mathcal{H}$	Hamiltonian function
J	performance index
n	number of revolutions
O	primary's center of mass
r	Sun–spacecraft distance (au)
t	time (days)
T	orbital period (days)
u	radial component of the spacecraft velocity (km/s)
v	circumferential component of the spacecraft velocity (km/s)
y	dimensionless parameter
α	cone angle (deg)
ΔV	velocity variation (km/s)
$\Delta\theta$	phasing angle (deg)
λ_i	adjoint to state i
μ	gravitational parameter $(\mathrm{km^3/s^2})$
τ	switching parameter

Subscripts

0	initial, parking orbit
1	perihelion, periapse
f	final
max	maximum
$\oplus$	Earth
$\odot$	Sun

Superscripts

$\cdot$	time derivative
$'$	depending on the controls

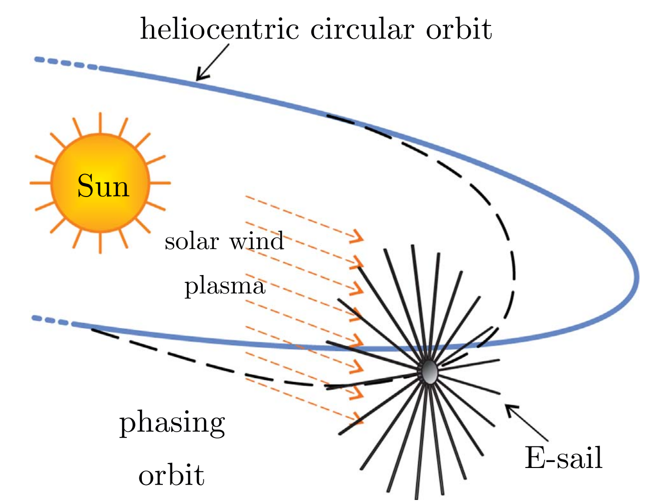

Fig. 1. In-orbit repositioning of a E-sail-based spacecraft: conceptual scheme. We assume a radial direction of the solar wind plasma propagation.

due to its high orbital inclination and eccentricity. On the other hand, a mission toward Lagrange's point L_5 is useful for monitoring the solar wind composition in order to forecast the geomagnetic disturbances with 4.5 days in advance [9]. Such a mission would make it possible to increase our knowledge about the interconnections between Earth and Sun through in situ measurements [10,11], thus extending the mission scenarios considered in the Living With a Star Program of NASA. In this context, an in depth discussion of the scientific implications obtainable with a helioseismic investigation of the solar magnetism is given in Ref. [12].

The paper is organized as follows. The next section briefly summarizes the conflicting requirements between the total velocity variation and the flight time necessary to obtain a prescribed phasing angle under the assumption of a bi-impulsive and tangential maneuver. This allows us to quantify the cost of the maneuver using a chemical thruster. Section 3 illustrates the option offered by an E-sail to fulfil a phasing maneuver, where the problem is addressed within an optimal framework by minimizing the total flight time using an indirect approach. Section 4 summarizes the simulation results obtained by varying both the reference value of the E-sail propulsive acceleration, and of the (mission) phasing angle. These results are then applied to different mission scenarios including a phasing maneuver along the Earth's heliocentric orbit, an estimate of the minimum flight times required to transfer a spacecraft from the Lagrange points L_1 to L_4 (or L_5), and a discussion about the convenience of using a drift ahead or a drift behind maneuver. Some final remarks conclude the paper.

2. Position of the problem

In a simplified mission scenario, the phasing maneuver is constituted by two impulsive velocity variations, both having the same velocity variation ΔV, and the transfer trajectory is an ellipse tangent to the circular parking orbit (of radius r_0) at its apocenter or pericenter, see Fig. 2. In particular, the maneuver is performed by applying two tangential impulses, that is, two impulses along the direction of the spacecraft orbital velocity vector.

2.1. Mathematical model

The total velocity variation ΔV can be expressed as a function of the phasing angle $\Delta\theta \in [-\pi, \pi]$ along the circular parking orbit. To that end, let $n \in \mathbb{N}^+$ be the number of revolutions covered by the spacecraft during the phasing maneuver, and introduce the dimensionless parameter

$$y \triangleq \frac{\Delta\theta}{2\,\pi\,n} \tag{1}$$

It can be verified that the corresponding value of the total velocity variation is

$$\frac{\Delta V}{v_0} = 2\left|\sqrt{\frac{2(1-y)^{2/3}-1}{(1-y)^{2/3}}} - 1\right| \tag{2}$$

where $v_0 = \sqrt{\mu/r_0}$ is the circular velocity along the parking orbit around the celestial body of gravitational parameter μ, whereas the total flight time Δt is

$$\frac{\Delta t}{T_0} = n - \frac{\Delta\theta}{2\,\pi} \quad \text{with } \Delta\theta \neq 0 \tag{3}$$

where T_0 is the orbital period of the parking orbit.

The case $\Delta\theta > 0$ refers to a spacecraft that drifts ahead (case A) a virtual point, along the circular orbit, which coincides with the vehicle's position at the beginning of the maneuver, see Fig. 2(a). On the other hand, the case $\Delta\theta < 0$ corresponds to a drift behind maneuver (case B) with respect to the same virtual point, see Fig. 2 (b). Note that the radius r_1 of the periapse in the case A (or the