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Drag and propulsive forces in electric sails with negative polarity

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Abstract

An electric solar sail (E-sail) is a recent propellantless propulsion concept for a direct exploration of the Solar System. An E-sail consists of a set of bare, conductive tethers at high positive/negative bias, prone to extract solar wind momentum by Coulomb deflection of protons. Additionally, a negatively biased E-sail has been proposed as a concept for de-orbiting space debris with drag forces produced in Low Earth Orbit (LEO). The present work focuses on the negative-bias case with a sheath that must be correctly modeled for a flowing plasma ambient. Ion scattering within the sheath and the resulting force are determined for several plasma conditions. Since the plasma flow does reduce the effective range for the ion scattering within the sheath, the resulting force is then reduced. Tethers at very high negative bias should be required for extremely high plasma flow.

Keywords: Electric solar sails; Tethers; Solar wind; Coulomb force; Lorentz force; Space debris

1. Introduction

Electric solar sail (E-sail) uses bare tethers in a new technology application, which involves Coulomb forces on charges instead of Lorentz forces on currents (Janhunen and Sandroos, 2007; Janhunen, 2009a; Janhunen et al., 2010; Sanchez-Torres, 2014, 2015a). Originally, tether bias ϕ_p was set positive but a negative bias allows for Coulomb force too (Janhunen, 2009b). An E-sail requires Coulomb force calculations under several plasma conditions. The Coulomb force calculation in both Low Earth Orbit (LEO) and the solar wind at 1 Astronomical Unit (au) heliocentric distance involves the relative motion with respect to the ambient plasma, $\mathbf{v}_{rel} = |\mathbf{v}_{orb} - \mathbf{v}_{pl}|$. Coulomb forces do produce thrust if the plasma velocity v_{pl} is larger than the orbital velocity v_{orb}, whereas it would be drag if $v_{rel} \simeq v_{orb}$. In both LEO and solar wind, tethers are in mesothermal flow, i.e. moving subsonic and supersonic with respect to electrons and ions, respectively (Liu, 1969).

Janhunen (2009b) determined a rough analytical formula of the thrust for negativelly biased tethers immersed in the solar wind plasma ambient. However, the high solar wind plasma flow was not considered there. Results in Janhunen (2009b, 2014) for negatively biased tethers show that the electron temperature does not affect the Coulomb force. In the present paper, plasma flow is considered for the force calculation. We will show here that plasma flow does reduce that force and the electron temperature will affect both propulsive and drag force in both LEO and solar wind plasma ambient.

Lorentz forces in tethers can be considered for reducing the constant risk of collision of space debris. Tethers design for de-orbiting LEO satellites at end of mission was recently studied by Sanmartin et al. (2015). Note that Lorentz forces are really small in the solar wind plasma ambient because of the small magnetic field, except if extremely large tethers are considered. Additionally, negativelly biased tethers might be used for space debris applications. Coulomb forces for satellite de-orbiting was considered by Janhunen (2014). Both Lorentz and Coulomb force in

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tethers were estimated for several plasma conditions (Sanchez-Torres, 2015a). Sanchez-Torres (2015b) estimated both forces in LEO for relativistic conditions due to tethers at extremely high positive bias. Solar wind conditions at 1 au, quite different from LEO conditions, make Coulomb forces dominant for tethers of about 10 km. However, Coulomb forces in LEO are smaller than Lorentz forces for a positively biased tether, whereas Lorentz forces can be smaller for shorter tethers with negative polarity (Janhunen, 2014; Sanchez-Torres, 2015a,b).

A review of the plasma ambient conditions in LEO and solar wind is presented in Section 2. In Section 3, we briefly study the forces acting on the E-sail. Both potential and density profiles of a single tether are determined in Section 4. The ion scattering problem in that potential profile and the resulting force on the tether are studied in Section 5. Conclusions are presented in Section 6.

2. Plasma ambient conditions

Typical values for the solar wind ambient plasma at 1 au in the ecliptic plane are $T_e \sim 12$ eV, $n_\infty \sim 7$ cm^{-3}, solar wind velocity, $v_{sw} \approx 400$ km/s, and magnetic field, $B \sim 10$ nT. This particular choice of plasma ambient values was considered here to compare results with Janhunen (2009b). The electron temperature T_e scales as $d^{-1/3}$ with the distance d from the Sun (Sittler and Scudder, 1980). The prevalent ion species in the solar wind is H^+. Density models become simply (Leblanc et al., 1998), $n_\infty \approx 7.2(1\ \text{au}/d)^2$ cm^{-3} beyond 1 au. In a simple isothermal outflow Parker model Parker, 1958, the averaged solar wind velocity increases slowly with distance from the Sun as $\sqrt{\ln d}$. In the solar wind plasma ambient the relative velocity is about two orders of magnitude greater than orbital velocity in LEO.

In LEO the electron temperature typically varies from 0.1 to 0.3 eV. The magnetic field at the equator in LEO altitudes is about 30 μT. Electron densities varies with the solar cycle, orbital inclination and altitude. In the 700–1000 km equatorial range, densities of about 3×10^5 cm^{-3} and 3×10^4 cm^{-3} could be found for maximum and averaged-cycle flux, respectively.

Unmagnetized plasma conditions in both LEO and solar wind cases will be considered in the present work for Coulomb force calculation. As it will be shown in the next section, discussing Coulomb and Lorentz forces involves two lengths, Debye length λ_D and v_{rel}/Ω_i, which need be compared to tether radius R and length L, respectively; Ω_i is the ion gyrofrequency, eB/m_i, being e and m_i the electron charge and the ion mass, respectively. A summary of typical values is presented in Table 1.

3. Coulomb-to-Lorentz force ratio

A vertical tether, which lies in the Earth's equator and the ecliptic plane for LEO and solar wind cases, respectively, is considered for an estimation of the Coulomb-to-Lorentz force ratio. The tether orientation will be perpendicular to plasma flow. Assuming a round wire of radius R, the Lorentz force on the length-averaged current $I_{av} = \kappa I_{coll}$ reads

Table 1
Typical values for the ambient plasma and characteristic lengths.

Localization	LEO	1 au heliocentric distance
v_{rel}	7.5 km/s	400 km/s
B	0.3 Gauss	10^{-4} Gauss
Species	O^+	H^+
T_e	0.1–0.3 eV	12 eV
n_∞	10^4–10^6 cm^{-3}	7.2 cm^{-3}
v_{rel}/Ω_i	10^2 m	10^6 m
λ_D	$5 \cdot 10^{-3}$ m	10 m
$0.5 m_i v_{rel}^2$	5 eV	1 keV

$$F_L \approx I_{av} LB, \quad I_{coll} \approx 2RL \times e n_\infty \sqrt{\frac{2e|\phi_p|}{m_i}}, \tag{1}$$

where bias has been taken uniform following the Orbital Motion Limited collection current, I_{coll}. The averaged current involves tether and ambient parameters which makes $\kappa \sim 0.5$ (Sanmartin et al., 1993). The Coulomb force F can be estimated as proportional to both frontal area and dynamic pressure

$$F \propto 2r_{sh}L \times n_\infty m_i v_{rel}^2, \tag{2}$$

where r_{sh} is the sheath radius. The Coulomb-to-Lorentz force ratio for negatively biased tether will then read (Sanchez-Torres, 2015a),

$$\frac{F}{F_L} \sim \frac{v_{rel}}{\Omega_i L} \frac{\lambda_D}{R} \frac{r_{sh}}{\lambda_D} \sqrt{\frac{m_i v_{rel}^2/2}{e|\phi_p|}}. \tag{3}$$

Typical lengths considered in the literature in solar wind plasma ambient are $L \approx 10$ km and $R \approx 20$ μm for tethers with $|\phi_p| \sim 10$ kV. In LEO, both ratios $v_{rel}/(\Omega_i L)$ and $m_i v_{rel}^2/|2e\phi_p|$ are small compared to unity, and λ_D/R is large. In the solar wind both ratios $v_{rel}/(\Omega_i L)$ and λ_D/R are large, whereas $m_i v_{rel}^2/|2e\phi_p|$ should be moderately small for an effective ion scattering. For high bias tether, $e|\phi_p|/(kT_e) \gg 1$, and $\lambda_D/R \gg 1$ the dimensionless ratio r_{sh}/λ_D is large in LEO and in the solar wind. The ratio m_e/m_i is small in both regions. Using typical values on Table 1 and tether lengths of about 5 km, Coulomb forces, determined by (2), are larger than Lorentz forces in both LEO and solar wind.

4. Potential profile for a single tether

For a positively biased tether, ion scattering occurs in the entire sheath where ions can not arise (Sanchez-Torres, 2014, 2015a). However, for a negatively biased tether, ion scattering does occur in a particular region within the sheath where the ion density is reduced and