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JOURNAL OF PROPULSION AND POWER
Vol. 20, No. 4, July–August 2004 (Tentative)

Technical Notes

Electric Sail for Spacecraft Propulsion

Pekka Janhunen*
Finnish Meteorological Institute/Geophysical Research, FIN-00101, Helsinki, Finland

Nomenclature

A = cross-sectional area of wire, m
A_s = total surface area of all wires, m^2
$A_s^{(1)}$ = surface area of one wire, m^2
a = acceleration, $m \cdot s^{-2}$
E = electric field along wire, V/m
e = electron charge, $A \cdot s$
F = force excerted by solar wind on system, N
I = total electron current to the mesh, A
I_1 = electron current to one wire, A
j = electron current density from plasma to wire mesh, $A \cdot m^{-2}$
$j_{\|}$ = maximum current density in wire, $A \cdot m^{-2}$
L = linear dimension of whole structure, m
m = mass of wire mesh, m
m_p = proton mass, kg
N = number of wires
n = solar wind plasma number density, cm^{-3}
P = power consumption of electron removal, W
p_{dyn} = solar wind dynamic pressure, nPa
r = radius of the mesh wire, m
V = mesh potential with respect to plasma, V
v = solar wind speed, m/s
v_e = thermal speed of solar wind electrons, m/s
v_{final} = final speed of spacecraft, m/s
ΔV = potential drop along wire, V
Δx = mesh spacing, m
ρ = mass density of wire material, $kg \cdot m^{-3}$
ρ_{SW} = solar wind mass density, $kg \cdot m^{-3}$
σ = wire material conductivity, $\Omega^{-1}\ m^{-1}$

I. Introduction

IT has been previously proposed that a magnetic sail, that is, an artificial magnetosphere, could be used for extracting solar wind
Q1 momentum for spacecraft propulsion purposes.[1,2] Here we consider an alternative approach, which does not require a magnetic field.

II. Electric Sail

Consider a mesh made of thin conducting wires and placed across solar wind flow (Fig. 1). If the mesh is kept at a positive potential with respect to the solar wind plasma, an outward electric field sets up around each wire whose spatial scale size is comparable to the Debye length of the plasma. Incoming solar wind protons see the mesh as an inpenetrable barrier if the mesh spacing is of the same order as the Debye length or smaller and if the mesh is kept at a potential V, which is such that eV exceeds the kinetic energy of the solar wind protons (about 1 keV). To be sure that the potential is high enough, we assume $V = 6$ kV.

Let r denote the radius of the mesh wire (where we assume $r = 5 \times 10^{-6}$ m) and $A = \pi r^2$ its cross-sectional area. Assume for simplicity that the mesh is a square with side length L and that the mesh spacing is Δx so that there are $N = L/\Delta x$ wires along each side. We assume $L = 30$ km and $\Delta x = 5$ m. The total length of wire in the structure is $2NL = 2L^2/\Delta x = 360{,}000$ km, and its mass m is

$$m = 2L^2 A\rho/\Delta x = 250 \text{ kg} \tag{1}$$

where ρ is the mass density of the wire metal. (We assume copper density $\rho = 8900\ kg \cdot m^{-3}$.) The (maximum possible) force F acting on the mesh structure is obtained by multiplying the solar wind dynamic pressure $p_{dyn} = \rho_{SW} v^2$ by the mesh area L^2, where $\rho_{SW} = nm_p$ is the solar wind mass density and v its flow velocity (proton ve- Q3
locity). We assume the average values at 1 astronomical unit (AU) $n = 7.3\ cm^{-3}$, $\rho_{SW} =$ and $v = 400$ km/s, where $p_{dyn} = 2$ nPa (Ref. 3). Q4
Thus, one obtains $F = \rho_{SW} v^2 L^2 = 1.8$ N. The acceleration a of the structure is

$$a = F/m = (\rho_{SW}/2\rho)(v^2 \Delta x/A) = 7 \times 10^{-3}\ m \cdot s^{-2} \tag{2}$$

A. Pumping Out Electrons

Solar wind electrons bombard the wire mesh, trying to neutralise its positive charge. Therefore, electrons must be continuously "pumped" out of the structure by attaching it to a voltage source whose other end is connected to an electron-emitting device (Fig. 1). The total surface area of the wire mesh is

$$A_s = (2N)2\pi r L = 4\pi r L^2/\Delta x = 11300\ m^2 \tag{3}$$

and the current density due to the thermal flux of solar wind electrons can be roughly estimated as $j = env_e$ where v_e is the solar wind electron thermal speed, we assume $v_e = 10^6$ m/s. We obtain $j = 1.2\ \mu A\ m^{-2}$. The total current I to the whole mesh is

$$I = env_e A_s = 13 \text{ mA} \tag{4}$$

In the voltage source, the current I goes through potential drop V, consuming power $P = VI = 80$ W. A useful measure of the power requirement is the power per mass ratio,

$$\frac{P}{m} = \frac{2Venv_e}{r\rho} = 0.3\ W\ kg^{-1} \tag{5}$$

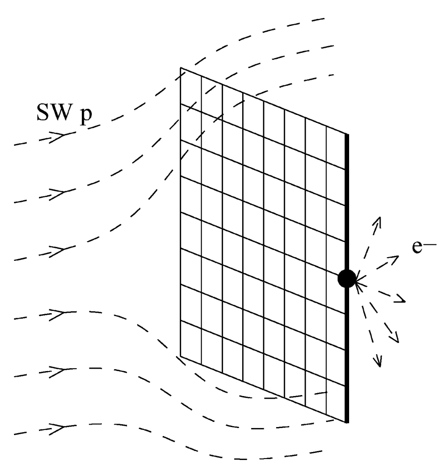

Fig. 1 Schematic of the electric sail.

Received 25 February 2004; revision received 11 March 2004; accepted for publication 12 March 2004.

Q2 *(**Job title**), (**dept.**), P.O. Box 503.

Table 1 Electric sail configurations

L, km	$2r$, μm	m, kg	a, $\mathrm{m \cdot s^{-2}}$	v_{final}, km/s	P	P_{wire}/P, %
30	10	250	7×10^{-3}	46	80 W	0.06
30	5	63	0.027	91	40 W	0.11
60	2.5	63	0.11	183	80 W	1
200	2.5	700	0.11	183	1 kW	10

Thus the power consumption is quite reasonable. Present-day solar-powered electric engines, SMART-1 [1] for example, reach a power per mass ratio of nearly 10 W $\mathrm{kg^{-1}}$ for the whole spacecraft. For comparison, a normal car reaches almost 100 W $\mathrm{kg^{-1}}$.

A possible problem may be that some electrons undergo collisions and are trapped in the potential wells around the wires. If these electrons become too numerous, their charge density partially shields the core positive charge, making the sail less effective in drawing momentum from solar wind protons. If this problem turns out to be severe, turning off the voltage periodically should help because then the electrons escape with the solar wind.

B. Power Consumption in the Mesh Itself

It is necessary to check also that each wire is separately capable of carrying the electron current without problems. Each mesh wire has length L, cross-sectional area $A = \pi r^2$, and surface area $A_s^{(1)} = 2\pi r L$. The electron current I_1 arriving to the wire is $I_1 = env_e A_s^{(1)} = 1.1\ \mu\mathrm{A \cdot m^{-2}}$. This current must flow through one end of the wire where it has a current density $j_\parallel = I_1/A = 14000\ \mathrm{A \cdot m^{-2}}$ along the wire. If the wire material conductivity is σ [where we assume copper conductivity in room temperature, $\sigma = 6.0 \times 10^7 (\Omega\mathrm{m})^{-1}$], the electric field along the wire is $E = j_\parallel/\sigma = 2.3 \times 10^{-4}$ V/m and the potential drop over the wire is $\Delta V = EL = 7$ V. (Actually this is a slight overestimate because the current density has the quoted value only at one end of the wire.) Thus, the wire gets heated at power $I_1 \Delta V = 8\ \mu$W. In total, all of the $2N = 12{,}000$ wires consume heating power 0.1 W, which is negligible.

C. Effect of Mesh Size and Wire Thickness

In Table 1, we show the mesh mass m, obtained acceleration at 1 AU under nominal solar wind conditions a, approximate final velocity $v_{\mathrm{final}} = \sqrt{[2a(1\ \mathrm{AU})]}$, total electric power consumption P, and fraction of power consumed distributed in the wire mesh rather than the voltage source. The first column is the mesh size L, and the second column is the wire diameter $2r$. In all cases considered, the last column value remains small. (In the last row it is 10%.) When this parameter is small, the acceleration is independent of the mesh size and the scaling of the system is trivial. Obtaining large accelerations and final velocities requires using thin wire, which is technologically more challenging than using a thicker wire. When the final velocity starts to be a significant fraction of the solar wind speed (400 km/s), the acceleration decreases because it is the velocity difference that drives the system, and the ultimate limit is the solar wind speed. This effect is ignored in Table 1.

D. System Shape

In the preceding rough calculations, we assumed a simple square shape for the wire mesh. Questions related to the shape, including how to keep the mesh in its desired shape, are very similar in the electrical sail to what they are when designing solar sails. Because solar sail designs have been studied by many authors, we do not dwell on the subject here.

III. Conclusions

The electric sail is a promising candidate for extracting momentum from the solar wind. Another way to use the solar wind momentum is to use a magnetic sail, which requires a superconducting one-dimensional loop wire of length somewhat smaller than the linear extent of the electric wire mesh L. The electric sail does not need any magnetic fields or superconductors, and its power requirements are modest. The technical challenge is how to manufacture, pack, transport to space, deploy, and maintain the desired shape and orientation of a very large mesh made of very thin wire. In any method relying on the solar wind momentum, one must live with the fact that the solar wind is highly variable. Accurate maneuvering is difficult, but the method should be well suited for missions whose purpose is just to travel fast out of the solar system across the heliosphere to interstellar space.

Acknowledgments

This work drew inspiration from an ESA-funded study of magnetic sails that was carried out at Finnish Meteorological Institute by the author and Petri Toivanen and Hannu Koskinen, with Alain Hilgers (ESA/European Space Research and Technology Center) acting as contact officer. These people are acknowledged for discussions and support.

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Queries

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