SPACECRAFT FORMATION CONTROL IN VICINITY OF LIBRATION POINTS USING SOLAR SAILS

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ABSTRACT

Vicinity of solar-terrestrial collinear libration points L1 and L2 is considered to be very attractive regions for exploration solar wind phenomena and their influence onto Earth magnetosphere. If spacecraft (s/c) is moving in L1 proximity it gives the possibility of early monitoring of solar wind disturbances with successive impact on magnetosphere processes. As it is known L1 point is located at ≈1.5 mln. km from the Earth on the Sun-Earth line on Sun side. This distance is determined by ratio of Sun and Earth gravitational constants. To move this point further from the Earth it is enough to decrease Sun attraction by some way. In the paper the use of solar sails for this purpose is explored. To control the motion of s/c the idea to use solar sails with variable transparency is considered. For this purpose the sails are proposed to be manufactured from two layers: one layer consists from liquid crystal film and the other – from foil with mirror reflecting surface. By applying variable voltage to the surfaces of liquid crystal film it is possible to vary the transparency of film. So ideally the reflectivity of film may be varied from zero (or full absorption of sails) to full reflection. As a result solar radiation pressure may be change from some minimum value corresponding full absorption to two times higher value for ideal mirror reflection. In the paper the methods of the use such approach for s/c motion control for the formation flight in the vicinity of libration point L1 and beyond are explored.

1. SOLAR RADIATION PRESSURE IMPACT ON SPACECRAFT MOTION IN VICINITY OF L1 POINT

If spacecraft (s/c) is put in L1 libration point it moves around Sun with the same orbital period as the Earth. In case if large enough solar sails are mounted on s/c the effect of solar radiation pressure is to be taken into account. Approximately position of s/c on the Sun-Earth line, supposing that the around Sun orbital angular rate is equal the Earth’s one can be calculating using the following formula:

\[ \omega (a - d) = \frac{\mu_S}{(a - d)^2} - \frac{\mu_E}{d^2} - \frac{F \cdot S}{m}, \]  

(1)
where: \(\omega\) – mean Earth heliocentric orbital angular rate;
\(a\) – Earth orbit semi major axis;
\(\mu_S\) – Sun gravitational constant;
\(\mu_E\) – Earth gravitational constant;
\(F\) – solar radiation pressure (N/m\(^2\));
\(S\) – s/c cross-section area (sails area);
\(m\) – s/c mass;
\(d\) – distance of s/c from Earth center.

For full photons absorption we have:

\[
2.6105.4 \cdot \left( \frac{a}{a-d} \right)^2 = -da \cdot aF. \tag{2}
\]

Using Eqns. 1-2 and assuming that \(\mu_S = 132712517 \times 10^3\) km\(^3\)/s\(^2\), \(\mu_E = 398.6 \times 10^3\) km\(^3\)/s\(^2\), \(a = 149597.81 \times 10^3\) km it is possible to calculate the required sails area to keep s/c at Earth-Sun line on the Sun side on the \(d\) distance from the Earth.

Results of these calculations for the case with full photons absorption (opaque sails surface) is given by table 1.

<table>
<thead>
<tr>
<th>(d), tds km</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m/S), kg/m(^2)</td>
<td>-</td>
<td>0.03468</td>
<td>0.02018</td>
<td>0.01502</td>
<td>0.01042</td>
</tr>
</tbody>
</table>

For the full reflectivity of sails surface acceleration produced by solar radiation pressure is two times higher. So for the same distance of s/c from the Earth the ratio of s/c mass to sails area can be increased by two times.

Thus with the solar sails it is possible to move position of L1 libration point further from the Earth as table 1 shows.

The same formula can be used for the case when s/c is put onto modified by solar radiation pressure L2 libration point: it is enough to change the sign of distance value \(d\), and Earth gravitational constant \(\mu_E\) onto negative one. Another quite obvious assumption here is that s/c moves on some trajectory near L2 out of Earth shadow.

## 2. CONSTRUCTION OF SPACECRAFT FORMATIONS IN VICINITY OF L1 POINT

Given above simple estimations show that with the use of solar sails it is possible to construct formation of s/c positioned along Earth-Sun line beyond L1 point on the different distances from the Earth.

To reach this it is enough to have either s/c with different mass to sails surface area either to change the reflectivity coefficient of the sails surface. The last method may be applied with sails including liquid crystal films.

In any case the maneuvering possibilities of s/c are necessary. As effective actuators for maneuvers solar sails are proposed to be used. For this purpose solar sails may be manufactured from two layers, one layer (on Sun side) is liquid crystal film and the other layer is mirror foil.
With the possibilities to change the ratio of mirror reflecting part of sails surface to the absorbing one we can change not only the value of resulting force but also the direction of this force without attitude variation. These features of sails with liquid crystal film are described by formulae:

\[ T_x = -T_0 \left( 2 (1 - k) S \cos^2 \varphi + k S \cos \varphi \right), \]  
\[ T_y = -2T_0 (1-k) S \cos \varphi \sin \varphi, \]  

(3) \hspace{1cm} (4)

where: \( T_x, T_y \) - projection of s/c acceleration, produced by solar radiation pressure onto \( X, Y \) axes of solar-ecliptic coordinate system; 
\( T_0 = F/m \); 
\( k \) - ratio of surface area with full absorption to the total area, it is suppose that the rest area has the ideal mirror reflectivity; 
\( \varphi \) - angle from \( X \) axis (Sun directed) to the vector orthogonal to the sail surface, it is suppose here that this vector lies in ecliptic plane.

Thus for executing maneuver with given acceleration components \( T_x, T_y \), it is enough to calculate \( k \) factor and \( \varphi \) angle by resolving Eqns.3-4. As to the third acceleration component \( T_z \) the approach is similar, but should be mentioned as it follows from [1], the maneuver for motion control in \( Z \) direction is more effective to fulfill on the other parts of orbit than for motion in ecliptic plane. Also it should be reminded that for the nominally uncontrolled part of the trajectory the nominal value of \( T_x \) is supposed with nominal \( T_y = 0 \). So if consider \( \Delta V \) maneuver as flight with some added to the nominal one acceleration, then for our case the maneuver acceleration along \( X \) is \( \Delta T_x = T_x - 2T_0 \).

3. SPACECRAFT FORMATIONS IN L1 VICINITY CONSTRUCTED WITH ONE IMPULSE TRANSFER

In this chapter libration point trajectories for the s/c equipped by solar sails are studied for the case when only one impulse is applied on the low Earth parking orbit in order to reach target orbit.

![Fig.1. Solar sails size impact on near L1 orbits.](image-url)
It is assumed that this orbit has inclination to equator equal $i=65^\circ$ and right ascension of ascending node $\Omega=0^\circ$. The date of injection is assumed to be 7 August 2005. Fig. 1 illustrates in solar-ecliptic coordinate system the s/c formation case when 3 s/c are launched using one impulse transfer trajectory: without sails, with sails corresponding $m/s = 0.07 \text{ kg/m}^2$ and sails with $m/s = 0.054 \text{ kg/m}^2$. Sails are assumed to be with ideal mirror reflection. Trajectories are calculated by numerical integration method for differential equations of s/c motion. The one impulse manifold of libration point trajectories are characterized by maximum amplitude along Y axis. At the point of injection the osculating parameters of the orbits are the same (eccentricity $e=0.99$, inclination towards equator $i=65^0$, perigee argument $\omega=10^0$, latitude argument $\nu=10^0$, eccentricity $e=0.99$, inclination towards equator $i=65^0$, perigee argument $\omega=10^0$, latitude argument $\nu=10^0$) besides semimajor axis equal 492494.5 km ($e=0.985$), 674810 km, 1070700 km for the listed above cases accordingly. Moving along those orbits s/c with the largest sails reaches up to 3400 tds. km distance from the Earth along Earth-Sun line (s/c without sails $\approx$ 1700 tds. km). Period of motion in XY plane for this s/c about 294 days what is $\approx$ 1.63 times longer than for s/c without sails.

4. RECONSTRUCTION OF FORMATION BY MANEUVERING WITH THE USE OF SOLAR SAILS
For solar wind monitoring it is important to fulfill the measurements of the particles which in their traveling from the Sun are candidates to reach the Earth. From this point of view it is necessary to put s/c more close to the line Earth-Sun. In other words the Y amplitude of libration point orbit is to be smaller than ones presented by Fig.1. For this purpose the orbital maneuver is required.

Figures 2, 3 illustrate the possibility to execute such maneuver using solar sails by changing reflectivity of sails and attitude of s/c for sails sizes corresponding $\frac{m}{s} = 0.07$ kg/m$^2$ and $\frac{m}{s} = 0.054$ accordingly. And Fig. 4 illustrate this for a s/c without using solar sails.

To illustrate the result of sequence of maneuvers looks like, on the Fig.5 final orbits (after maneuvers) of s/c are also given.

Thus the result corresponds to basic requirements of possible physical experiments.

REFERENCES