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Attitude Control Requirements for Various Solar Sail Missions

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Summary

This paper summarizes the differences between the attitude control requirements for various types of proposed solar sail missions (Earth-orbiting; heliocentric; asteroid rendezvous). In particular, it is pointed out that the most demanding type of mission is the Earth-orbiting one, with the solar orbit case quite benign and asteroid station-keeping only slightly more difficult.

It is then shown, using numerical results derived for the British Solar Sail Group Earth-orbiting design, that the disturbance torques acting on a realistic sail can completely dominate the torques required for nominal maneuvering of an 'ideal' sail. This is obviously an important consideration when sizing control actuators; not so obvious is the fact that it makes the 'standard' rotating vane actuator quite unsatisfactory in practice. The reason for this is given here, and a set of new actuators described which avoids the difficulty.

Solar Sailing History:

- *Concept:* originally described by Tsiolkovsky.

- *in-flight experience:* (all for attitude torque generation, not propulsion).

  Mariner 4: limited use of 'fans' on solar array tips.

  Mariner 10: significant use of differential solar array rotation to balance roll disturbance torques. Use of this technique allowed the full mission to be flown, despite a gyro resonance problem that wasted enough propellant to threaten it.

  OTS-2: European Space Agency (ESA) communications spacecraft test article in GEO.

- *Proposed propulsion demonstrations:*

  JPL Halley's Comet rendezvous: rejected in favor of electric propulsion (later itself dropped).

  ESA Halley's Comet rendezvous: essentially a scaled-down version of the JPL sail, proposed for launch on an Ariane test vehicle.

  Amateur Earth-orbiting sails: for instance, the French U3P group's proposal for 2 or 3 sails to be launched on the Ariane 4 test vehicle and then race to the Moon's orbit. This stimulated research in various countries (e.g. Japan; Czechoslovakia; Great Britain [British Solar Sail Group]). A similar race has recently also been proposed by the AIAA to commemorate Columbus' mission in 1492. Another group very active in amateur sail design is the Pasadena-based World Space Foundation, which proposed a sub-scale version of the JPL sail in low Earth orbit.

Various Solar Sail Missions:

- *Heliocentric:* for example, the proposed rendezvous missions with Halley's Comet.

  Such missions are the least demanding from the point of view of attitude control. Orbit-raising requires a constant angle between sail normal and orbital radius : this leads to slow maneuvering, as well as simple sensor requirements.

- *Earth-orbiting:* e.g., the various proposed amateur sails.

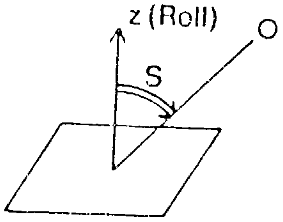
  More demanding, as the required sail attitude now changes throughout the spacecraft orbit. The required maneuver rates are thus much higher than in the previous case (although still very low by "conventional" standards). Sensor requirements are also more complicated, as the desired sail attitude is not now fixed relative to the Sun (or Earth).

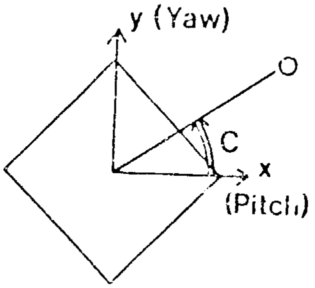
- *Asteroid reconnaisance:* There is currently great interest in studying the minor bodies in the Solar System. A result of this is the decision to target all NASA outer planet missions to at least one asteroid fly-by, with Galileo being the first spacecraft to do this. Considerably greater information could be obtained by long-term study of one or more asteroids from a spacecraft station-keeping with it.

  Such a mission appears to be well suited to solar sailing. Once boosted to Earth escape (by conventional chemical propulsion), the flight would decompose into: a heliocentric portion (Earth to sphere of influence of first asteroid target), with properties as outlined above; a phase involving maneuvering into orbit about the asteroid, with properties comparable to high-altitude Earth-orbit flight. The work of [3] for ion propulsion indicates that a modest sail would be adequate. Reboost and rendezvous with subsequent targets would be done in an entirely similar fashion.

Real vs. Ideal Sail Properties:

- *Ideal sail dynamics:* quite simple. If the sail is assumed to be **perfectly reflective** and **flat**, the solar force is always perpendicular to the sail plane, with magnitude $F = 2pA\cos^2 S$, where $p = 4.65\times10^{-6}$ N/m^2 at 1 A.U.:





Note that F is independent of C; furthermore, as the solar force acts along the roll axis, no roll torque can be generated by e.g. center of mass offsets.

- *Real sail dynamics:* the main difference is that any real sail has non-zero absorptivity a_s, leading to a more complicated solar force with a down-Sun term. In the coordinates above,

$$\mathbf{F} = -pA|\cos S|\,(a_s\sin S\cos C,\ a_s\sin S\sin C,\ (2-a_s)\cos S)^T.$$

Not only is this more complicated than the ideal sail force, but roll torques <u>can</u> now be generated by a shift in the center of pressure relative to the center of mass. If this shift is $(x, y, z)^T$, then the resultant torque is

$$\mathbf{g} = pA|\cos S|\begin{pmatrix} za_s\sin S\sin C - y(2-a_s)\cos S \\ x(2-a_s)\cos S - za_s\sin S\cos C \\ a_s\sin S(y\cos C - x\sin C) \end{pmatrix}. \quad \longleftarrow \text{[Small, but } \neq 0]$$

Disturbance Torque Sources:

- *Typical disturbance mechanisms:* (Details depend on the orbital parameters and design of the sail considered.)

  Center of pressure shift: this would result, for instance, if different parts of the sail degrade (increase in absorptivity) at different rates. LDEF results on the effects of exposing aluminized Kapton to the space environment should help quantify this.

  Center of mass shift: a typical way this can come about is as a result of thermal bending of the booms which support the sail. Such bending can be considerable, even for small thermal gradients across the booms, because of their great lengths. This results in a solar angle-dependent C.M. vs. C.P. shift.

  Gravity gradient torques: can be significant for Earth-orbiting sails.

  Spacecraft initial asymmetries: e.g. variability in the mass properties of sail and boom material and in the reflectivity of sail material; imperfect control of the deployment angles of booms, leading to a slightly unsymmetrical deployed sail.

  Negligible effects:

  - Boom bending caused by solar *radiation pressure* rather than solar *heating.*

  - Force due to the solar *wind* rather than photon pressure. (The solar wind pressure is about 4 orders of magnitude weaker than that of the photons.)

  - Atmospheric drag and magnetic torques: negligible at the high altitudes required for any Earth-orbiting sail.

Disturbance Torque Numerical Results:
The BSSG Sail Design.

- *Outline sail design:* aluminized Kapton sail of area 2400 m^2, supported on 4 GFRP booms and deployed using a simplified 'wrap-rib' technique. Total spacecraft mass of 200 kg gives a modest sail acceleration of about 10^{-4} m/s^2, sufficient for demonstration purposes. (For more information of the design philosophy and details of the British Solar Sail Group design, see [1] and [2].)

- *Predicted worst-case disturbance torques:* (from [2])

Cause of torque	Max. roll (Nm)	Max. pitch/yaw (Nm)
Sail degradation	3.76×10^{-5}	6.77×10^{-4}
Boom thermal bend	5.44×10^{-6}	2.44×10^{-4}
Gravity gradient	0	1.11×10^{-4}
Initial asymmetry	3.35×10^{-5}	6.97×10^{-4}
TOTAL:	7.65×10^{-5}	1.73×10^{-3}

- *Observations and implications:*

(1) These disturbance torques are considerably greater than the nominal steering torques required for an ideal sail, even for the relatively demanding Earth-orbiting BSSG mission.

(2) The gravity gradient torque is predictable; that due to thermal bending is calculable if the booms are instrumented, e.g. with strain gauges. The remaining torques, which make up the bulk of the total, result from a nearly **constant** center of pressure/center of mass shift.

(3) The roll disturbances are much lower than those in pitch and yaw. It is therefore inefficient to have actuators which can provide roll torques as large as those in pitch/yaw.

"Traditional" Radiation Pressure Actuators:

- *Variable-angle vanes:* the only extensive in-flight radiation pressure attitude control experience to date, i.e. Mariner 10 and OTS-2, was carried out as an 'add-on', using existing spacecraft hardware. These spacecraft used tiltable solar panels as solar pressure vanes, and this type of actuator has been used extensively in many solar sail designs (e.g. the JPL and ESA square sails both had rotating vanes at the boom tips). However, the preceding disturbance analysis points up some severe practical limitations of this type of actuator:

  Roll sensitivity: such vanes must be sized for the required pitch/yaw torques, but produce roll torques of the same magnitude. A misalignment of the vanes of just 1° can thus be shown [2] to give rise to a roll torque as large as all other disturbance sources combined.

  Duty cycle: as already noted, most sail disturbances result from a slowly-varying center of pressure/center of mass shift. They thus vary with solar angles S and C as given by the equation for g on page 4 with x, y and z roughly constant. But the torque produced by a rotating vane varies with **its** solar angles, not those of the sail. Thus, using a set of rotating vanes to counteract even a constant C.P./C.M. shift will require frequent vane rotations, complicating the control problem and reducing motor lifetimes.

- *In-plane ballast masses:* this technique, incorporated into the WSF sail for pitch/yaw, avoids the above problems. In particular, a constant C.M./C.P. offset is now easily compensated for by a constant offset of the ballast mass. It is important to note though that, as the disturbance torques dominate the nominal maneuver torques, the ballast mass must be sized with the disturbances in mind. This will typically result in a requirement that the ballast mass be allowed to move along the entire length of the booms.

Novel Radiation Pressure Actuators:

- *Variable-area vanes:* these avoid some of the problems of variable-angle vanes. A pair of 'roller-blind' vanes mounted on the tips of two adjacent booms and parallel to the sail plane would allow a constant C.P./C.M. shift to be compensated for by a <u>constant</u> vane offset. This greatly simplifies the problem of sequencing actuator commands. Furthermore, no large roll torque errors are produced by this arrangement; the undesirable coupling of the rotating vanes is avoided. A third small vane normal to the sail plane would now suffice for counteracting the low roll disturbances acting on the sail.

- *Product of inertia modulation:* this makes use of a mass on a variable-length boom mounted at the end of a sail boom and moving normal to the sail plane. This allows the spacecraft to be made <u>controllably</u> unbalanced: e.g. the product of inertia I_{xz} can be altered as required, so coupling the pitch and roll axes. The result of this is that a commanded pitch torque gives rise to an 'effective' roll torque of specified size. This technique may have applications to 'standard' spacecraft; in the BSSG design, the CCD camera was used as the movable ballast mass.

- *Phased roll control:* for a real sail, two actuators are actually adequate for pitch, yaw and limited roll control, which is all that is required. From the expression for **g** with $z = 0$, it can be seen that a (small) roll torque is produced by altering x and y. The ratio of roll torque to pitch/yaw torque is proportional to tanS, and so is small for small S and large for S approaching 90^{o}; furthermore, it can be of either sign. As a result of this, modulating e.g. y about the average value needed for pure pitch control can produce pitch plus roll control; for instance, if a larger net roll torque is required, setting y low for small S and high for S in the range 50^{o}-70^{o} or so would achieve this.

Summary:

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References

[1] T.W.C. Williams and P.Q. Collins, 'Design Considerations for an Amateur Solar Sail Spacecraft', Paper IAF-83-395, 34th IAF Congress, Budapest, Hungary, Oct. 1983.

[2] T.W.C. Williams and P.Q. Collins, 'Attitude Control System and Communications Payload for an Amateur Solar Sail Spacecraft', Paper IAF-84-363, 35th IAF Congress, Lausanne, Switzerland, Oct. 1984.

[3] M. Guelman, 'Orbital Rendezvous with an Asteroid', Paper AAS 89-428, AAS/AIAA Astrodynamics Specialist Conference, Stowe, Vermont, Aug. 1989.

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