Solar Sail Attitude Dynamics and Coning Control to Attain Desired Orbital Effects

Farheen Rizvi
Mail Stop 230-104
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, CA 91109-8099
California Institute of Technology
Farheen.Rizvi@jpl.nasa.gov
(818) 354-1324

Solar sails are an attractive solution for expensive and massive space missions. Traditional spacecraft must carry in-space propulsion fuel that increases both launch mass and cost. A sail exposed to solar radiation offers free and continuous propulsion by manipulating the sail thrust vector direction relative to the sun. This makes long mission durations feasible. For example, one application proposed a sail for study of the Earth's magnetotail. This required the spacecraft orbit to continuously rotate to follow a sun-synchronous path and also raise its orbit to explore the entire magnetotail. Free solar propulsion via a sail proved an optimum propulsion system over conventional chemical or electric propulsion due to the reduced mission mass and cost.

Orbit changes result from orienting the thrust vector, which requires the attitude of the sail to be controlled. Sails typically contain a small spacecraft bus in the midst of a large, gossamer structure. Most sail work has addressed feasibility concerns related to orbit analysis and structural sail dynamics. Due to its size, significant solar, aerodynamic and gravity gradient torques act on the sail and can disturb the sail orientation (attitude) relative to the sun. Accordingly, large control torques are needed to counteract these attitude disturbances, and an understanding of sail attitude dynamics is required in order to design appropriate control algorithms.

Recent studies have analyzed natural sail dynamics in order to maintain the desired thrust vector pointing. Generally, large external torques are required to maintain desired thrust vector pointing relative to the sun. But it has also been shown that specific kinds of torques can be generated naturally under the influence of solar, aerodynamic and gravity gradient torques. This reduces the need for expensive and massive traditional attitude control techniques (attitude jets or reaction wheels). The basic idea is to operate at attitude equilibria of the sail normal vector (sail normal) in the local vertical local horizontal (LVLH) frame. An extension of this idea is to utilize a slight deviation of the sail normal from these equilibria, which results in sail normal coning about that equilibrium. This sail normal coning is illustrated in the following figure.

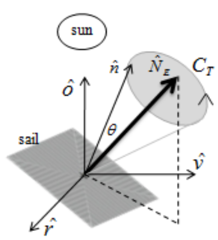

Figure: Sail normal coning about the LVLH equilibrium attitude ($\hat{N}_E$). *With a slight deviation from the equilibrium attitude (θ), the normal vector ($\hat{n}$) will trace a coning trajectory (C_T). Cone tracing should occur at orbit rate to attain desired sail orbit changes.*

These sail normal coning results show that any desired sail orbit changes can be obtained with sail normal coning at orbit rate (circular cones).

In this study, a controller is designed that can achieve sail normal coning at orbit rate to attain the desired orbital effects. The natural dynamics of a rigid, uniform, flat and square solar sail under the influence of aerodynamic, solar and gravity gradient torques is investigated. The natural dynamics is incorporated with an attitude controller that enables the sail normal vector to track the desired coning trajectory. The controller determines the additional torque required to track the trajectory. A feasibility study is performed to determine a practical method for applying the additional torques via external sources (e.g via magnetic coils) or internal sources (via sail bus motion). As opposed to other attitude control techniques, this approach is interesting because it produces smooth sail rotation rates that do not disturb the structural sail dynamics. In addition, this approach allows desired orbit changes to be attained with less expensive attitude control hardware.