

A “YANK AND YAW” CONTROL SYSTEM FOR SOLAR SAILS

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L’Garde sail designs use vanes for stability and control. A vane control scheme is presented which takes advantage of passive stabilization, in an aircraft-like arrangement. All four vanes are first “Canted” anti-sunward for passive stability about the two beam axes. The Cant angles of the fore and aft vanes are retrimmed to maneuver to a new passively stable attitude about the port-starboard axis, similar to “yanking” and retrimming aircraft elevators. The port and starboard vanes are differentially “Twirled” about the beam axis to maneuver and actively stabilize the vehicle about the sun-sail line, similar to “yawing” an aircraft via the rudder. These two maneuvers can be performed sequentially in any order, or simultaneously. Additionally, the neutral Twirl angle of the port and starboard vanes can be retrimmed to move an axis of stability from the fore-aft axis to a line perpendicular to both the sail-sun line and the port-starboard axis, the “SSXPS” axis. Passive stability about the port-starboard axis and about SSXPS couple to passively stabilize about the sail normal. The sailcraft is thus always flown “fore beam into the wind,” guaranteeing sail shape symmetry about the fore-aft axis, and the method can be extended to fly “any beam into the wind.” Advantages of this scheme are repeatability of propulsion, safe operation with full control authority, control system simplicity, and low cycle time with propellantless redundancy.

INTRODUCTION

First, reference coordinate systems are defined, followed by discussion of how vane Cant and Twirl are used for stability and control. An example implementation is also presented, with maneuvering and stability response curves.

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REFERENCE COORDINATE SYSTEMS

The body-fixed coordinate system “Sail” is illustrated below. The analogy is an aircraft flying over the surface of the sun. The aircraft’s belly is the reflective side.

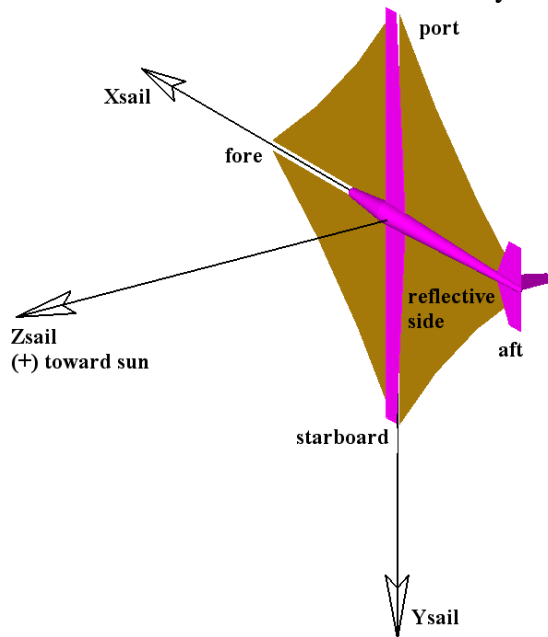


Figure 1 Body-Fixed “Sail” Coordinate System

“Sun Incidence” is the angle between the sail normal (Z_{sail}) and the sail-sun line.

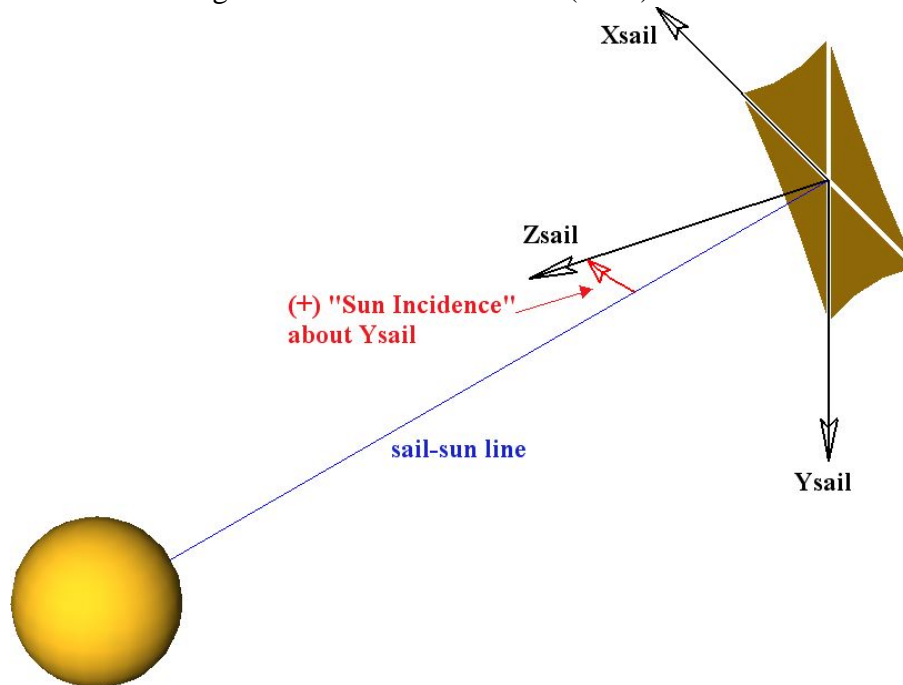


Figure 2 “Sun Incidence” Angle Between Sail Normal and the Sail-Sun Line

“Flatspin” is the rotation about the sail normal, Z_{sail} . For an idealized flat plate sail, forces and moments would not change with Flatspin. However, for a real sail, forces and moments will change somewhat due to sail billow, particularly asymmetric sail billow, as well as variations in relative beam bends.

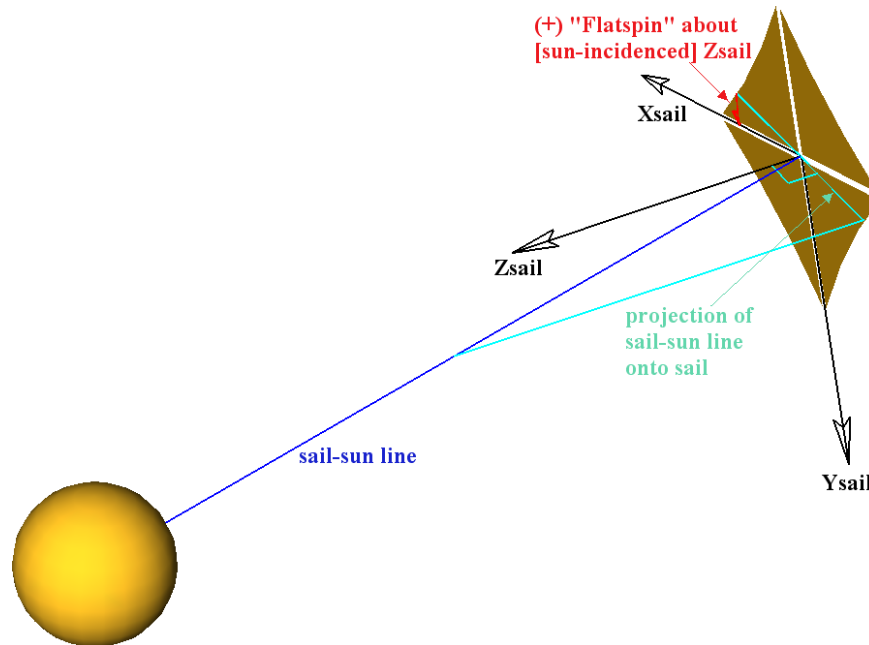


Figure 3 “Flatspin” Angle

“Top” is rotation about the sail-sun line, relative to the “Sun” frame, described below.

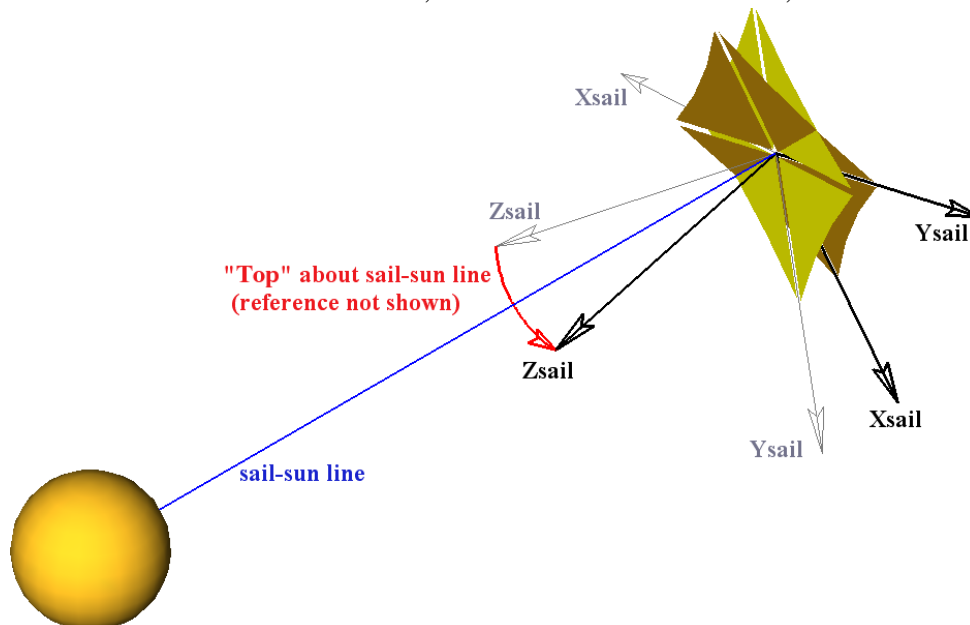


Figure 4 “Top” Angle Rotation About the Sail-Sun Line

For full specification, the sun-sail line must be located in an inertial frame (here the J2000 frame), a reference for Top specified, and the solar distance known. The attitude of the sail-sun line in J2000 may typically be specified using “Right Ascension” and “Declination.” In order to establish a reference and sense for Top and to facilitate transformations, a new coordinate system is introduced, the “Sun” system. This system moves with the sail, its origin coincident with the “Sail” system origin. Zsun always points toward the J2000 origin, along the sail-sun line. Xsun is defined as parallel to the J2000 x-y plane, and Ysun completes the orthogonal set.

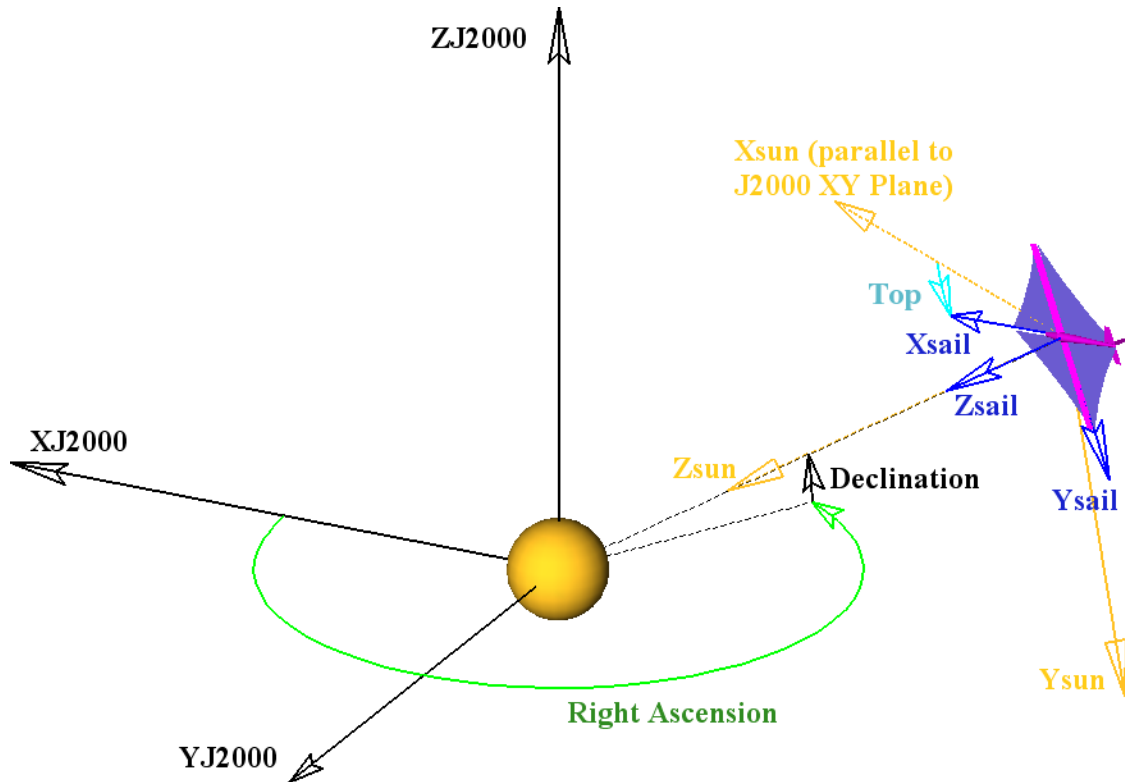


Figure 5 Placement in an Inertial Frame

The orientation of the Sun system relative to J2000 is defined by the following Euler sequence:

“Flip” -90° about x \rightarrow - (“Right Ascension” + 90°) about y \rightarrow - “Declination” about x

To rotate from the Sun system to the Sail system:

Top about z \rightarrow Sun Incidence about y \rightarrow Flatspin about z

Sail Shape Asymmetries and Repeatability of Propulsion

One can achieve any available thrust direction using Sun Incidence and Top alone. Propulsive changes with Flatspin are small, and are due primarily to sail billow. Sail billow shape is an "aeroelastic" problem, as the local sail angle will affect the solar and inertial forces, which will in turn alter the shape, which again gives new forces. Off-zero Sun Incidence will entail some asymmetric sail billow. However, sail shape symmetry about one beam axis is still preserved if Flatspin is 0° , 180° ; 90° , or 270° , although each angle may have a slightly different shape due to beam manufacturing variations. This can be done by keeping either the Ysail or Xsail axis perpendicular to the sun-sail line.

For repeatability of propulsion, that is, to get the same thrust and direction each time for a certain Sun Incidence angle, the Yank and Yaw technique keeps Flatspin at 0° or 180° . Considering sunlight as a "wind", and ignoring vehicle velocity, the fore beam (the (+) Xsail axis) is pointed "into the wind" whenever Sun Incidence is negative (and Flatspin = 0°). The Ysail axis is always perpendicular to the sun-sail line, and sail shape is symmetric about the Xsail axis. With two-axis control on all four vanes, the vehicle can be flown at Flatspin = 90° and 270° as well.

VANE CANT FOR STABILITY & TRIM, AND SUN INCIDENCE MANEUVERS

All sails with the center of mass forward of the center of pressure experience some passive stability about the two in-plane axes due to the solar "drag" force of an imperfectly reflecting sail, and sail billow imparts more stability due to the effective shuttlecock angle. L'Garde sails uses beam tip vanes Canted antisunward for passive stability and trim. The mass of the vane fields contribute appreciably to propulsion.

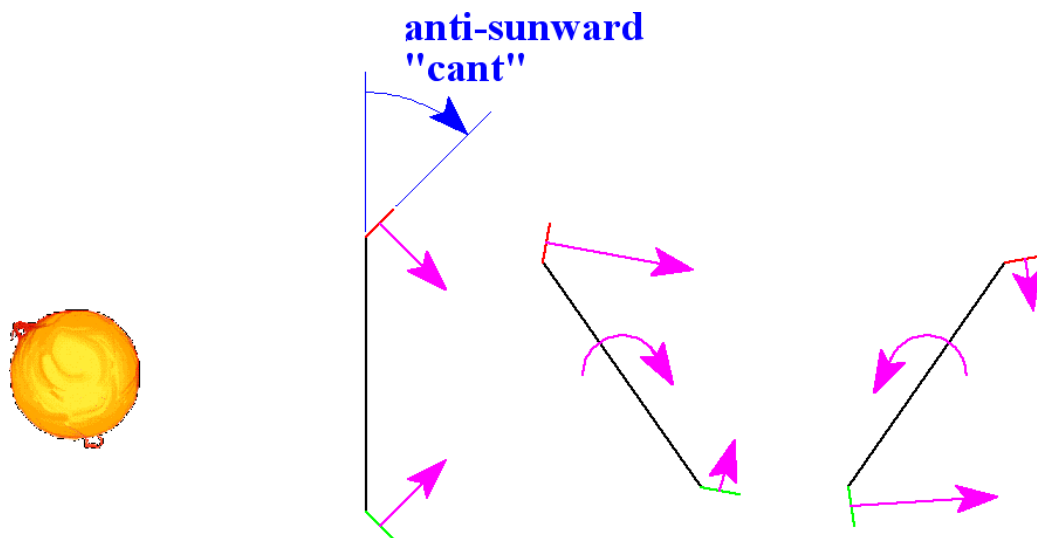


Figure 6 Passive Stabilization due to Canted Vanes

By varying the Cant angles of the fore and aft vanes, the Sun Incidence trim angle can be changed.

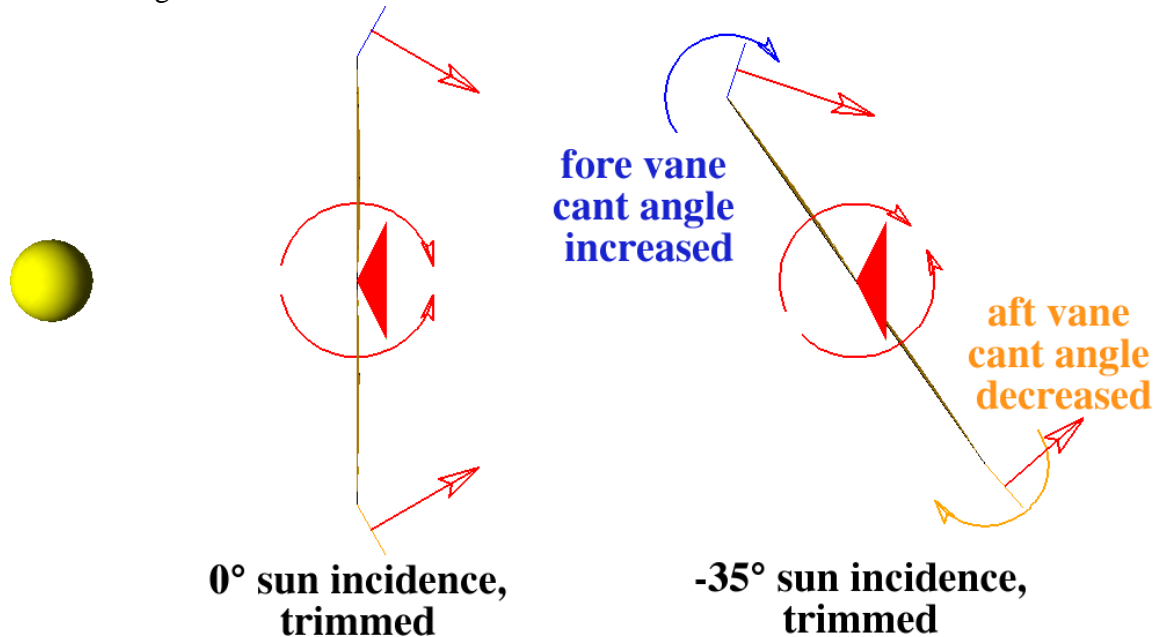


Figure 7 Retrim of Sun Incidence Angle

Safe Operation with Full Control Authority

Sailcraft turtle must be avoided. Sail temperatures would soar, and sailcraft attitude control would have a tough time of recovery. Even if one could right the ship, the sun-Earth line might be irreparably lost in the meantime (in the case of non-Keplerian orbits, the most mentioned type which might desire much higher than 35° Sun Incidence). More practical limits are the “luff limit”, the angle at which the aft sail quadrants begin to shadow, approximately 86° Sun Incidence., or the “jibe limit”, at which the free edges of the forward sail quadrants would suddenly reverse billow, approximately 104° Sun Incidence. Anyway, once the luff limit has been reached, thrust magnitude is reduced to less than 0.5% of sail-normal. It is hard to imagine the utility of such a deep stall condition in a non-Keplerian orbit, while it is easy to imagine the ensuing navigation nightmares. Also, well before that, at $\sim 73^\circ$ Sun Incidence, the radial thrust dominates, cone angle reaches its max of $\sim 58^\circ$, and thrust direction can no longer be maintained. That said, when using vanes rather than the mainsail to effect rotations, full control force is available at high Sun Incidence, as the vanes are articulated independently. This may be useful, for example, to effectively shut off the sail while another vehicle attempts to dock.

Avoiding 90° or 180° excursions is generally not possible for conventional spacecraft, which do not possess passive stability nor high mass moment of inertia. A

solar sail, on the other hand, has both time and stability on its side. Yank and Yaw maintains the port-starboard axis perpendicular to the sunline passively via port-starboard vane cant, and does not allow overdriving of the fore and aft vanes when changing Sun Incidence angle. That is, the fore and aft vanes are simply retrimmed to the Cant angles necessary for the new desired Sun Incidence angle. This is done in steps based on initial rotation rate to prevent overshoot. This basic approach is common in aircraft control. Further protection is gained using vane stops and rugged hardwired watchdogs observing vane angles and vehicle attitudes and rates. The fore and aft vanes are thus used more like aircraft elevators, rather than spacecraft thrusters. Failures or outages of the vane drives or attitude control electronics during a maneuver can be tolerated without approaching the luff limit. Additionally, even with a crippled vane, the cant of the opposite vane can be altered to compensate.

Cant of the port and starboard vanes passively maintains the port-starboard axis perpendicular to the sun-sail line, thus luff or jibe or turtle in this direction is avoided as well.

Yank and Yaw is directly applicable to orbit transfer missions, where application of Sun Incidence and Top maneuvers is straightforward. It is equally applicable to non-Keplerian stationkeeping, such as for L1 Diamond, as navigation laws utilize the natural thrust vectoring capabilities of the sail, that is, they specify cone and clock angles, and Yank and Yaw directly controls these two angles. Also, thrust magnitude can also be lowered while maintaining average direction by doing S-turns, as with an aircraft approaching landing. Full authority is also available for Earth-orbiting demonstration missions.

It must be stated that sailcraft agility is directly a function of sailcraft areal density. Sailcraft moment of inertia is almost insensitive to payload mass, as it is centralized. However, the lower the linear density of the beams for a certain sail size, and the thinner the sail membrane, the lower the moments of inertia, and the smaller the control devices need be for the same agility. Alternatively, for the same payload and performance, a smaller, lower moment of inertia sailcraft may be used. Lighter sails are more agile.

VANE TWIRL FOR TOP MANEUVERING AND ACTIVE STABILIZATION

As it is not possible to passively stabilize Top rotation about the sun-sail line, active Top angle stabilization and control is necessary whenever the Sun Incidence angle is nonzero. This is done by differentially “Twirling” the port and starboard vanes about their boom axis. The vanes in this case have to be used like spacecraft thrusters.

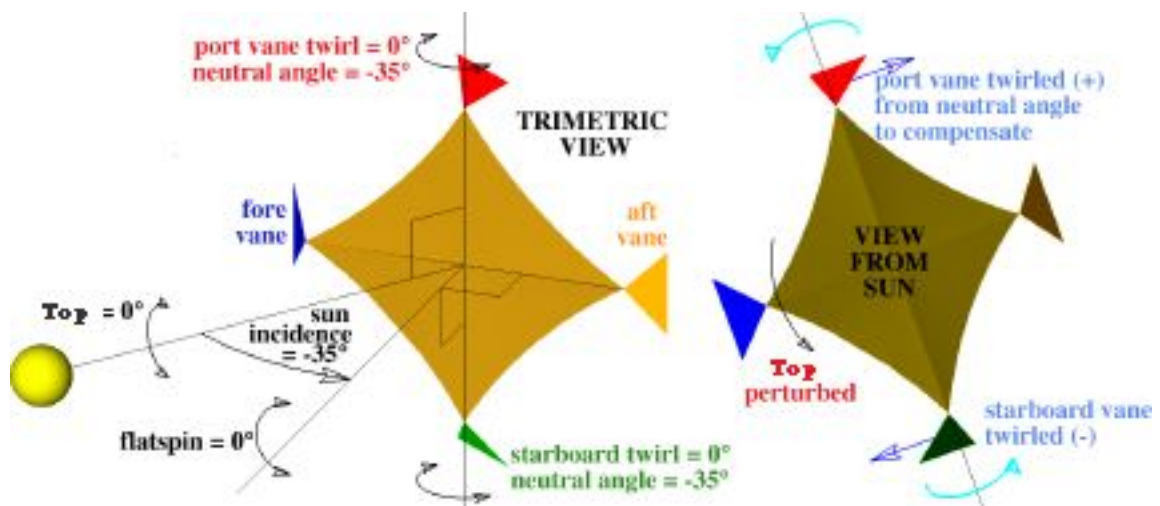


Figure 8 Active Top Angle Stabilization via Vanes

NEUTRAL TWIRL RESET FOR COUPLED FLATSPIN STABILIZATION

Port and starboard vane Cant stabilizes the port-starboard axis perpendicular to the sun-sail line. The axis of stability is in the plane formed by the sun-sail line and the fore-aft axis, depending on the neutral twirl angle. With Yank and Yaw, when a new Sun Incidence trim is set, the active Top stabilization system will also reset the neutral Twirl angle of the port and starboard vanes to the Sun Incidence angle. This moves the axis of stability from the fore-aft axis to a line perpendicular to both the sail-sun line and the port-starboard axis, the “SSXPS” axis. Passive stability about the port-starboard axis (provided by fore and aft vane cant, trimmed) and about SSXPS couple to passively stabilize about the sail normal (to maintain Flatspin = 0°), but this coupling will only occur only when the Sun Incidence angle is nonzero. The greater the Sun Incidence, the greater the Flatspin stability. At zero Sun Incidence, the sail normal is coincident with the sun-sail line, Flatspin and Top are one and the same, and there is no passive Flatspin/Top stability.

By switching the sign of Sun Incidence, or the roles of the port-starboard and fore-aft vanes, Flatspin can be stabilized at 180°, 90°, or 270° as well.

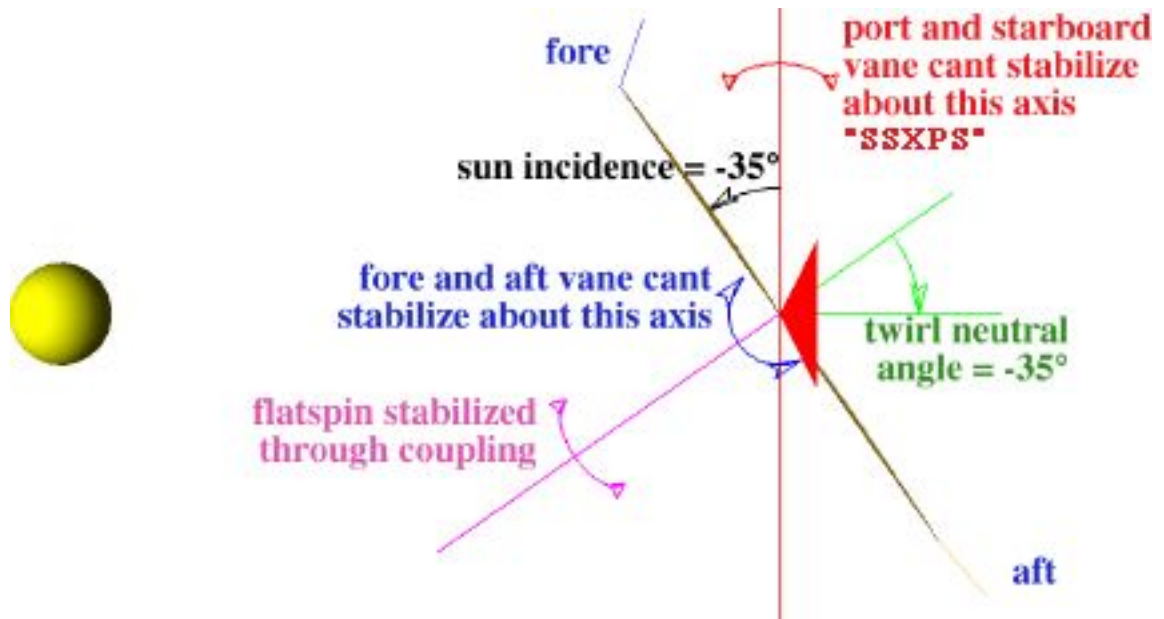


Figure 9 Passive Flatspin Angle Stabilization

TWIRL->CANT VS. CANT->TWIRL TYPE PORT-STARBOARD VANE YOKES

The port and starboard vanes (at least) are articulated in two axes, Twirl and Cant. Two types of yoke designs are possible. They are identified by the Vane Euler rotation sequence relative to Beam Tip as either:

“Twirl” about x -> “Cant” about y

or,

“Cant” about y -> “Twirl” about x

Positive sense is determined by the right-hand rule.

This selection refers to the implementation of Cant and differential Twirl only. In order to offset the neutral Twirl angle, a Twirl articulation about the beam axis is necessary. The Cant->Twirl yoke would require a third actuator, becoming:

Neutral Twirl -> Cant -> Differential Twirl

One type of yoke or another may produce better results for a particular implementation and mission set.

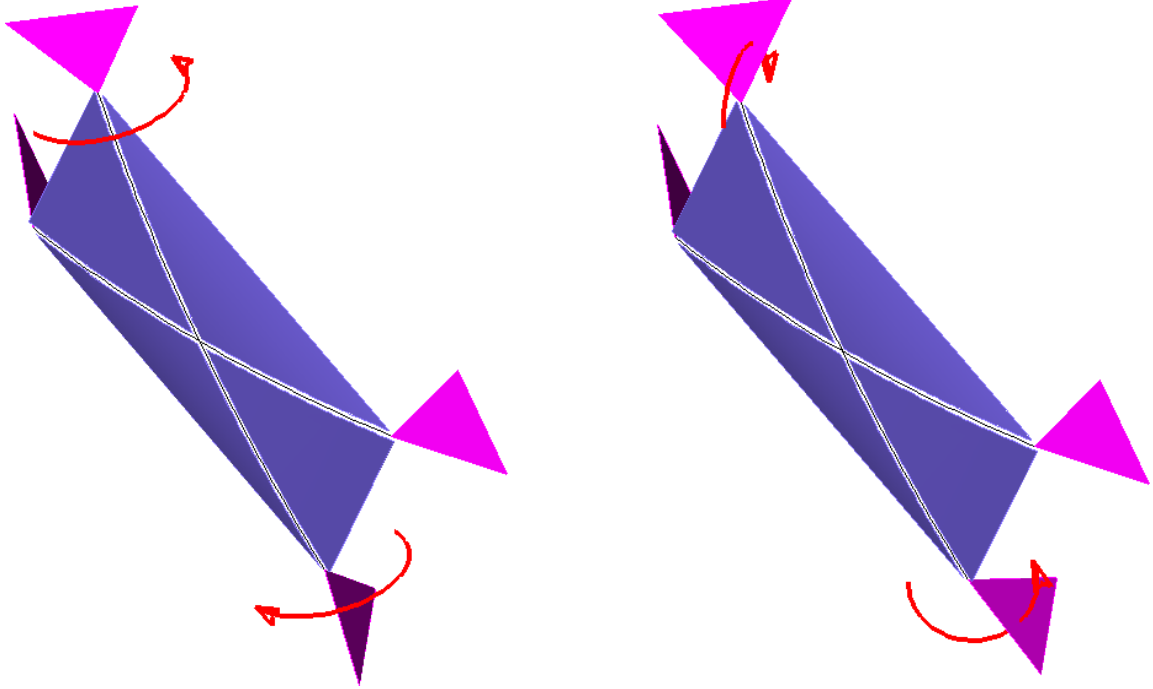


Figure 10 "Twirl->Cant" Type 2-Axis Yoke

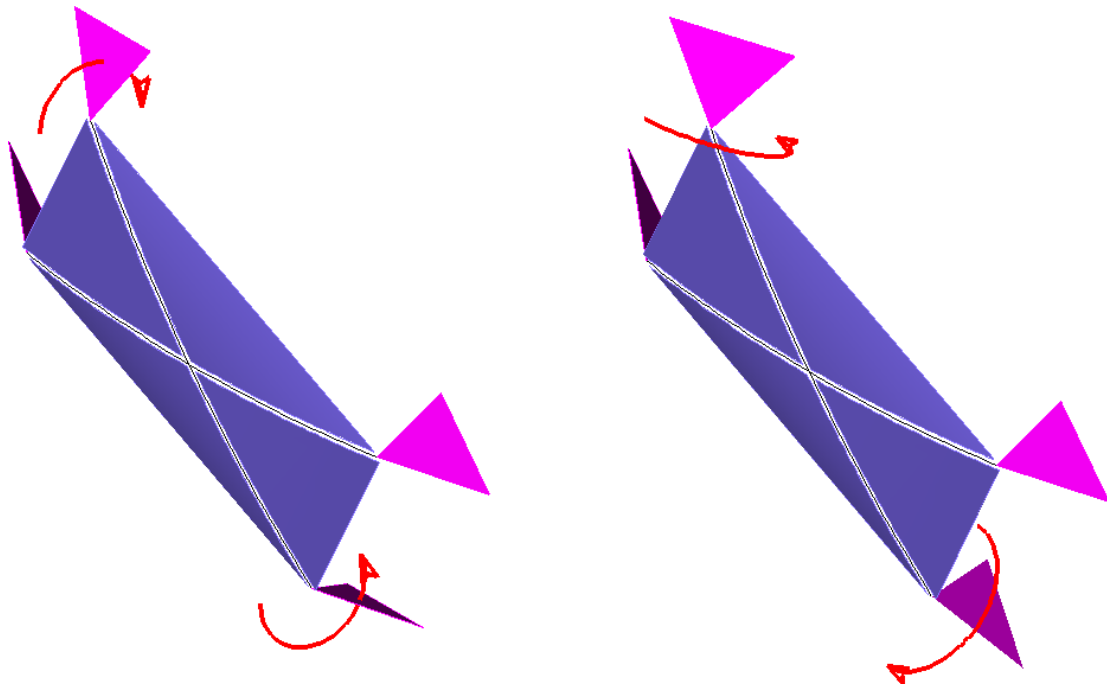


Figure 11 "Cant->Twirl" Type 2-Axis Yoke

EXAMPLE IMPLEMENTATION

Many hardware implementations are possible, but if one takes a distributed approach, an example hardware set is as follows:

1. Cant-only yoke for the fore and aft vanes
2. Twirl->Cant yoke for the port and starboard vanes
3. Sun Sensor and Sun Incidence Controller:
 - The angle about the port-starboard axis is used to set fore and aft vane Cant angles, based on the Sun-Incidence maneuver command, the current angle, solar distance, and lookup tables. The tables are updated to account for any biases due to imperfect or asymmetric sail shape.
 - The angle about SSXPS is passively stabilized to zero, but any deviation from zero, such as due to asymmetry-produced moments, is trimmed out.
 - Communicates Sun Incidence to the Top Controller
 - A watchdog circuit kicks in to avoid luff limit in anomalous operation.
 - May also serve as backup solar distance measurement
4. Star Camera and Top Controller:
 - Camera used to determine Top angle
 - May also serve as backup to the sun sensor.
 - Actively controls and stabilizes Top angle using differential port and starboard vane Twirl.
 - Keeps the neutral Twirl angle = Sun Incidence
 - Trims out any bias moments in Top
 - Can override Sun Incidence Controller in case of anomaly
5. Tracking, Guidance, and Navigation:
 - Determines position (Right Ascension, Declination, and solar distance)
 - Generates Sun Incidence & Top commands based on position & velocity
 - Delivers solar distance to Sun Incidence and Top Controllers

The cant drive on all four vanes is also used to deploy the vane from its stowed position. Once the sailcraft is deployed, it undergoes a calibration period where vane tables are updated to counter bias moments, and thrust magnitude and cone & clock angles (Ref. 1) vs. Sun Incidence and Top calibrated. As the sail will only be flown at Flatspin = 0°, perhaps 180°, calibration is significantly easier and shorter. Calibration will be sensitive to solar distance, and possibly to age, so will be periodically repeated or updated during flyout or operation.

Maneuvering

For passive stability, all four vanes are nominally canted anti-sunward 30°. Fore and aft vane Cant angles are varied from 30° to retrim Sun Incidence.

Table 1 Fore and Aft Vane Cant Angles vs. Trim Sun Incidence
4900 m² Flatsail with 12.7 m² Vanes

| fore vane Cant° | aft vane Cant° | Sun Incidence° |
|-----------------|----------------|----------------|
| 30 | -30 | 0 |
| 33.5 | -26.5 | -5 |
| 36.9 | -23.1 | -10 |
| 40.4 | -19.6 | -15 |
| 43.8 | -16.2 | -20 |
| 47.2 | -12.8 | -25 |
| 50.5 | -9.5 | -30 |
| 53.8 | -6.2 | -35 |

The most desirable Sun Incidence angle, especially for orbit transfer missions, is probably ~35° (cone angle = 32.4°), as this gives the greatest thrust component normal to the sun-sail line, generally the most useful component to effect inclination or orbit change in a circular orbit.

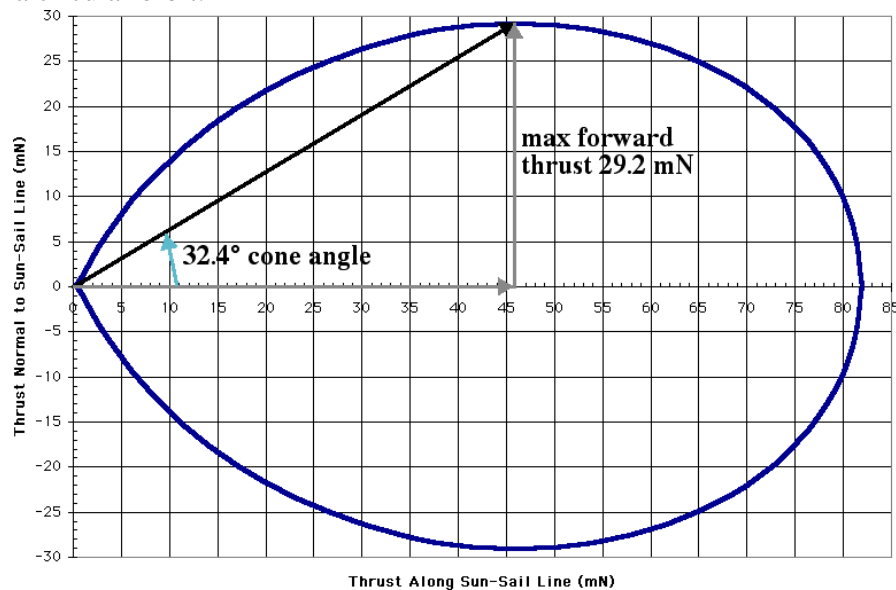


Figure 12 Polar Plot of 10,000 m² Flatsail Thrust at 1 AU vs. Cone Angle
(Sun is on the Left)

To maneuver Sun Incidence angle from 0° to -35° , with zero initial rotation rate, the fore and aft vane Cant angles are first set to effect a -17.5° trim Sun Incidence. Vane rotation generally takes less than a minute. From 0° to -17.5° , the sail is accelerating. From -17.5° to -35° , the sail is decelerating. Just before -35° is reached, the vanes are retrimmed for -35° Sun Incidence. There is no overshoot. With initial rates in the direction desired, the initial trim setting would be for, say, 10° Sun Incidence, to avoid overshoot. Such retrim with acceleration and deceleration phases is often used on aircraft.

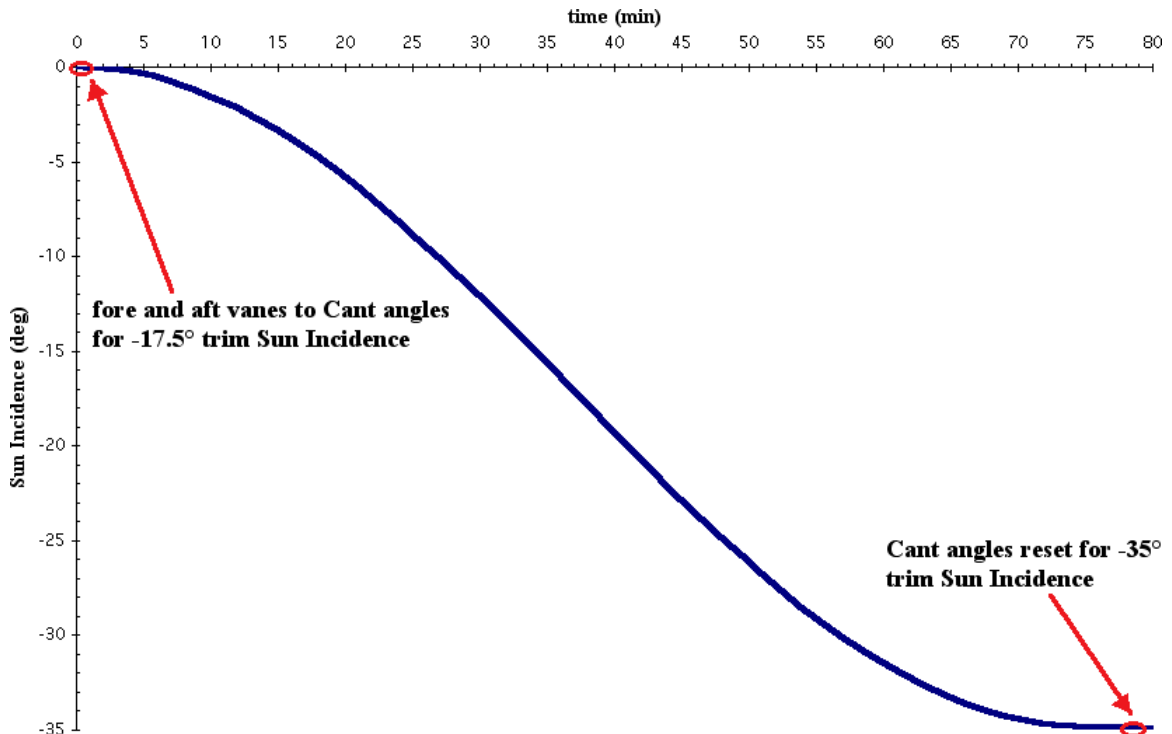


Figure 13 Sun Incidence vs. Time
4900 m² Flatsail with 12.7 m² Vanes

In this example, even if the vanes were somehow suddenly rotated to the stops, the vehicle would not approach the 86.6° luff limit, even without any damping at all.

It is easy to see how this method can be extended to modulate thrust magnitude without changing thrust direction. The vehicle would “S-turn” about a neutral Sun Incidence angle, as an aircraft approaching landing. Such thrust modulation has been deemed desirable for certain missions, especially Geostorm. It can be done safely, without approaching the luff limit of the sail.

A similar approach is used to perform a Top maneuver. Port and Starboard vane Twirl angles are differentiated $\sim\pm 35^\circ$ from the neutral angle for maximum force normal to the beam axis. Half way through the maneuver, each vane is rotated 70° to the opposite side to begin deceleration. Finally, near the maneuver end, the vanes are returned to the neutral Twirl angle. This is similar to a spacecraft firing a thruster one direction, then the opposite.

With Flatspin restricted to 0° or 180° , the largest Top maneuver required would be 90° .

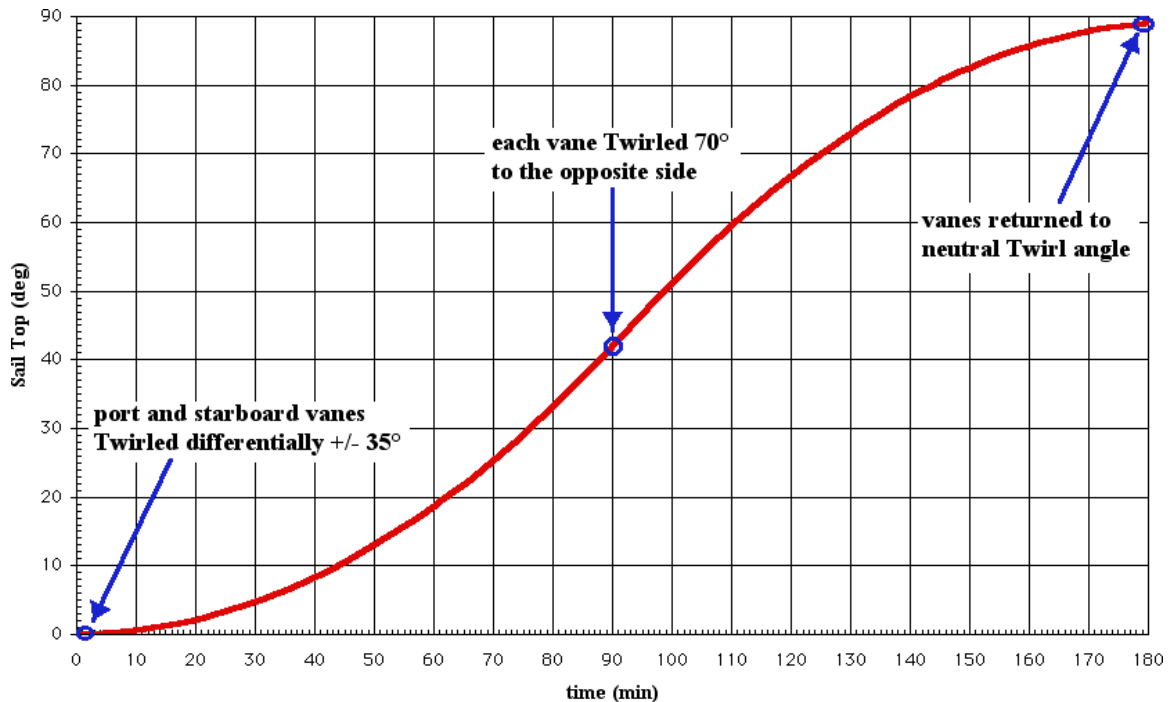


Figure 14 Top vs, Time
10,000 m² Flatsail with 30.4 m² Vanes

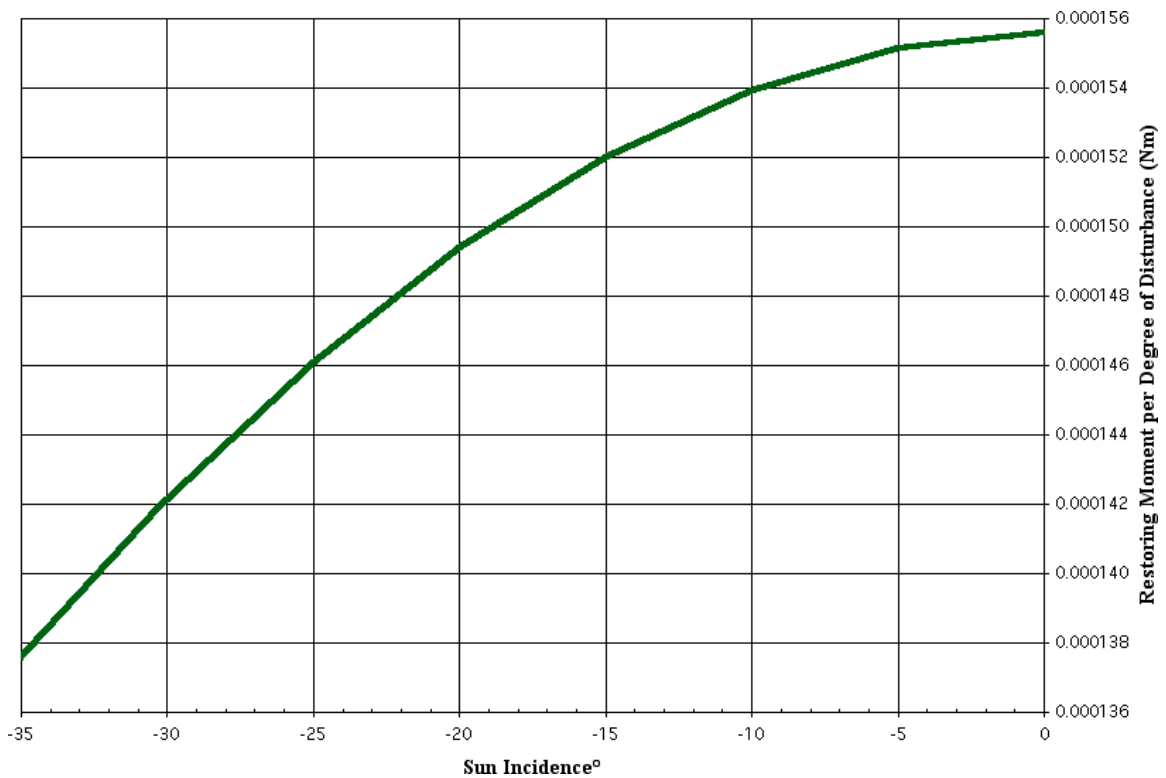
Top and Sun Incidence maneuvers may be performed in any order. Sequential maneuvers produce the cleanest turn, but simultaneous Top and Sun Incidence maneuvers are possible.

When the sail is at Sail Incidence, there is a cross product of inertia about the sun-sail line in the XZ plane. In a Top maneuver, this can give rise to rates about SSXPS. Rates will generally be decelerated in the second half of the maneuver, but the potential exists for residual angles. Passive static stability counters this, but it may be desirable to increase resistance to this motion by altering the Cant angles of the port and starboard vanes during a Top maneuver.

In response to the vane side load effecting a Top maneuver, the beams will sway in-plane, altering the shape and mass properties of the sailcraft somewhat, and producing a small moment arm acting in Flatspin. A more significant moment arm is presented when using a Twirl->Cant type yoke. This Flatspin effect is also decelerated, but again could result in a residual angle. Coupled passive stability resists this, but additional stiffness could be gained by having two-axis yokes on the fore and aft vanes, and differentially Twirling them during a Top maneuver.

Stability Response and Bias Trim

When disturbed from the trim angle by some amount, passive restoring moment appears about the port-starboard axis (Sun Incidence), about SSXPS, and about the sail normal (Flatspin).



**Figure 15 Sun Incidence Restoring Moment per Degree of Disturbance at 1 AU
4900 m² Flatsail with 12.7 m² Vanes**

The vehicle center of mass is slightly forward of the sail center of pressure, creating stability due to the “drag” force of an imperfectly reflecting sail. Also, sail billow essentially “shuttlecocks” the entire sail, creating stability in the same way as the vanes. These effects are overcome at nonzero Sun Incidence by adjustments to the Cant angles of the fore and aft vanes.

Manufacturing variations and deployment effects may create an in-plane offset between the center of pressure and center of mass. This will be reacted by adjusting Cant angles, possibly with slight differential and/or neutral Twirl as well.

Stiffness variations beam-to-beam could result in a bias moment about an axis in the XZ plane, somewhere between the sail normal and the sun-sail line. Passive Flatspin and active Top stability counter this. They can be trimmed by adjusting the neutral Twirl angle and the differential Twirl angle. Optionally, with two-axis yokes fore and aft, differential Twirl could be used to more directly counter Flatspin biases.

The sail will experience asymmetric billow at nonzero Sun Incidence. Biases due to quadrant-to-quadrant variations would most likely occur about the sun-sail line. This would be directly canceled by adjusting differential Twirl of the port and starboard vanes. The potential for this bias is significantly reduced by restricting operational Flatspin angles, thus preserving symmetry about the fore-aft axis.

Control System Simplicity

By separating the functions of Sun Incidence and Top maneuvering to fore-aft and port-starboard vane sets, respectively, and by directly controlling these two angles, the primary angles affecting propulsion and thrust vectoring, control system logic is simplified. Flatspin affects propulsion as well, but is passively stabilized. Maneuvers consist of simple acceleration-deceleration cycles.

Low Cycle Time with Propellantless Redundancy

Fore and aft vane Cant will see little change, normally only to effect maneuvers. Even if there is a failure, Cant of the opposite vane can be altered to compensate. The port and starboard Twirl drives will probably see the most action, in order to actively stabilize Top angle about the sun-sail line. These drives will of course be made highly robust and redundant, but in the event of failure, a propellantless redundancy is available. If a two-axis drive is used on the fore and aft vanes, the roles of the two axes can be reversed, flying “starboard or port beam into the wind”, with the fore and aft Twirl drives taking over for Top stabilization and control.

CONCLUSION

Advantages of Yank and Yaw are repeatability of propulsion, safe operation with full control authority, control system simplicity, and low cycle time with propellantless redundancy. When combined with a high-performance lightweight mainsail design, an agile, safe craft is possible. Solar sails possess relatively high moment of inertia and the potential for passive stability about all axes except the sun-sail line. It may be better in some cases to treat them as aircraft, rather than as spacecraft.

REFERENCES

- 1) McInnes, C.R., *Solar Sailing Technology, Dynamics and Mission Applications*, Springer-Praxis, London, UK, 1st Ed.