Factoring Thrust Uncertainty into Solar Sail Performance Validation

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Abstract

Many solar sail mission development groups use the concept of "ideal" solar sails for initial mission concept proposal. This may be appropriate for very early feasibility sizing, however some concepts being considered for funded studies or potential flight opportunities may be presenting overly optimistic capabilities for solar sail missions. Use of a more "realistic" solar sail model, addressing both thrust performance and sailcraft trajectory control, would ensure that concept feasibility and required developments and potential mission success are better reflected.

1. Introduction

In the early 2000s, NASA's In-Space Propulsion (ISP) program at the Marshall Space Flight Center (MSFC) conducted significant development of solar sail technology, resulting in the fabrication and vacuum deployment testing of two different 20-meter size sail configurations. In addition to this system development, ISP supported two different efforts to develop solar sail simulation software packages to model sailcraft characteristics and performance to allow better solar sail mission planning.

This paper summarizes these "realistic" solar sail performance factors, and demonstrates how these should be incorporated into future solar sail mission planning. Recommendations on operations to characterize the actual performance of a solar sail propulsion system, either for a demonstration or operational mission, will also be described. In addition, recommendations for pursuing potentially more palatable initial solar sail missions are also provided.

2. Material and methods

This paper leverages sail characteristic information gathered during the ISP developments, and one of the simulation packages, and focuses on identifying and estimating factors that may detract from the expected performance of a "perfect" solar sail. Most of the information presented is from the author's PhD studies and dissertation [1].

3. Theory and calculation

A popular source describing solar sails, characteristics and forces, steering methods, and equations of motions for orbit propagation is given in [2].

3.1 "Perfect" sail

A "perfect" sail is represented by a flat surface that provides complete reflection of incident solar radiation, as depicted in Figure 1. In this case, the total incident (f_i) and reflected (f_r) photon forces imparted on the surface create a total force (f_{tot}) that is perpendicular to the flat sail surface (in the normal direction).

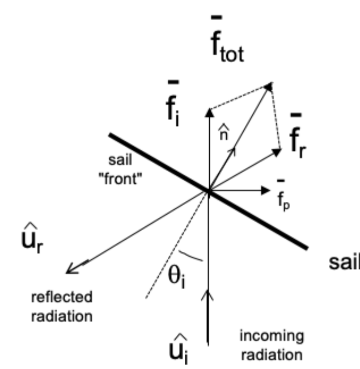

Fig. 1. "Perfect" solar radiation pressure force

This force can be calculated by Eq. 1, where θ_i is the incidence angle of the incoming solar radiation, P_i is the incident radiation pressure based on the solar luminosity energy flux (dependent on distance from the Sun), and A is the total area of the reflective surface.

$$\bar{f}_{tot} = 2P_I A\left(\cos\theta_i\right)^{2}\hat{n} \qquad (1)$$

Figure 2 shows the change in total force magnitude with changing incidence angle for a 100 x 100 meter square perfect surface at a 1 A.U. distance from the sun.

3.2 Non-ideal optical surface

Realistic surfaces have optical properties that affect the reflection of incident radiation. These properties include reflectivity (r_f), transmissivity (t_r), absorptivity (a_b), specularity (s), front and back emissivities (ε_f and ε_b), and front and back Lambertian reflection properties (B_f and B_b). Table 1 shows values for both and ideal surface and an example non-ideal sail surface (from ISP solar sail developments).

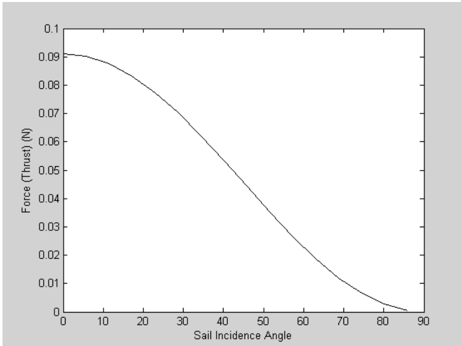

Fig. 2. "Perfect" solar radiation pressure force vs. sun-incidence angle (10,000 m^2 area @ 1 A.U.)

Table 1. Ideal and non-ideal optical properties

	t_r	a_b	r_f	s	ε_f	ε_b	B_f	B_b
Ideal sail	0	0	1	1	0	0	2/3	2/3
Non-ideal sail	0.02	0.1	0.88	0.94	0.05	0.55	0.79	0.55

Figure 3 shows the case of a solar sail with a flat surface, but with non-ideal optical characteristics.

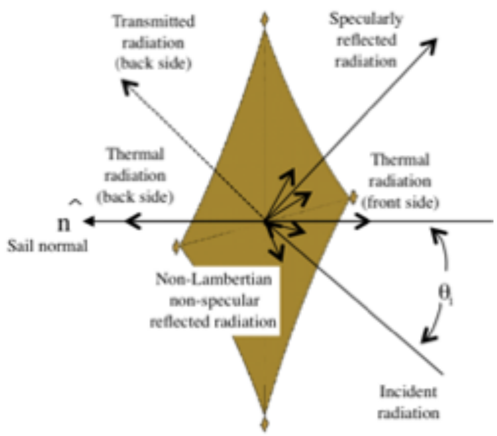

Fig. 3. Non-ideal optical solar sail

In this case, the incident radiation is not simply spectrally reflected, with some of the radiation transmitted, absorbed, and thermally and non-spectrally radiated from the surface. Incorporating these optical properties, the total force can be calculated using the following equations:

Normal force:

$$\bar{f}_n = P_l A\left[\left(1+r_f s\right)\cos^2(\theta_i)+B_f\left(1-s\right)r_f\cos(\theta_i) +\left(1-r_f\right)\frac{\varepsilon_f B_f-\varepsilon_b B_b}{\varepsilon_f+\varepsilon_b}\cos(\theta_i)\right]\hat{n} \tag{2}$$

Tangential force:

$$\bar{f}_t = P_l A\left(1-r_f s\right)\cos(\theta_i)\sin(\theta_i)\hat{t} \tag{3}$$

Total force:

$$f_{tot} = \left(f_n^2 + f_t^2\right)^{1/2} \tag{4}$$

Centerline angle:

$$\tan(\phi) = \frac{f_t}{f_n} \tag{5}$$

Figure 4 updates Figure 1 for this non-ideal case, and illustrates that the resulting total force is now offset from the normal direction by the centerline angle (ϕ). Note that for practical purposes the angle from the sun-line to the force direction is used for solar sail navigation, and is called the "cone" angle (α) as also shown. As we will show, this force angle from the sun-line has limitations.

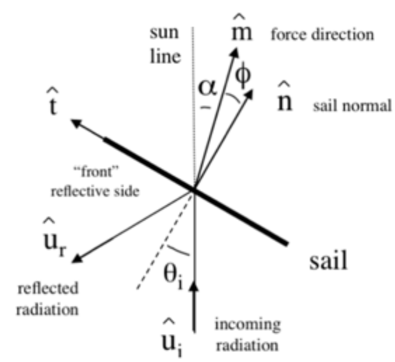

Fig. 4. Non-ideal optical solar radiation pressure force

Figure 5 compares the change in total force magnitude with changing incidence angle between this non-ideal sail and the same size ideal sail, showing a decrease in performance.

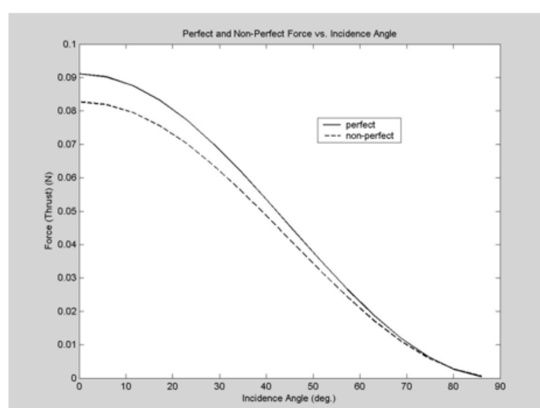

Fig. 5. Solar radiation pressure force vs. sun-incidence angle comparison (10,000 m^2 area @ 1 A.U.)

More importantly, Figure 6 plots the change in cone angle with increasing sun-incidence angle. As can be seen, due to the non-ideal optical properties there is a maximum angle that the force vector can be pointed away from the sun-line. This can have an impact on possible operation of the solar sail as a propulsion system.

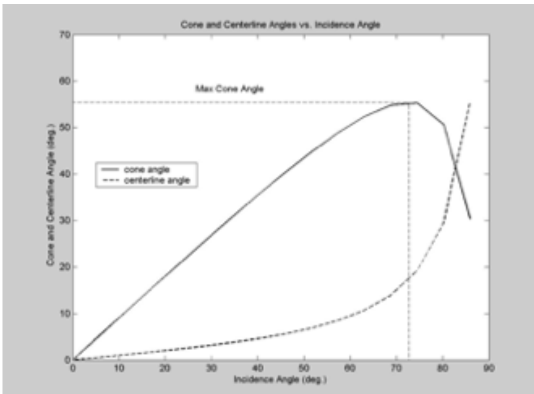

Fig. 6. Non-ideal sail cone angle vs. sun-incidence angle

Figures 7 and 8 plot impacts of changes in the surface optical properties, specifically for a 20% change from the example property values provided in Table 1. Figure 7 shows the impact on sail total force (thrust) magnitude, and Figure 8 the impact on thrust direction. As can be seen, surface reflectivity has the largest impact on both thrust magnitude and direction, however specularity also has a significant impact on force direction.

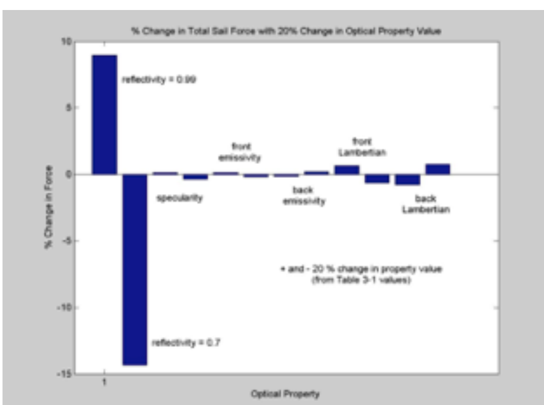

Fig. 7. Relative effects of optical properties on sail thrust magnitude

3.3 Sail shape

In addition to non-ideal optical properties, realistic solar sails will likely not have perfectly flat surfaces. Figures 9 and 10 show pictures of two different solar sail prototypes developed for the ISP program. Figure 9 shows a "tensioned" sail, pulled at its corners, and Figure 10 is a "draped" sail, more loosely supported by wires between the sail booms. (This latter approach intended to reduce the stiffness required by the booms, potentially reducing overall sail mass.)

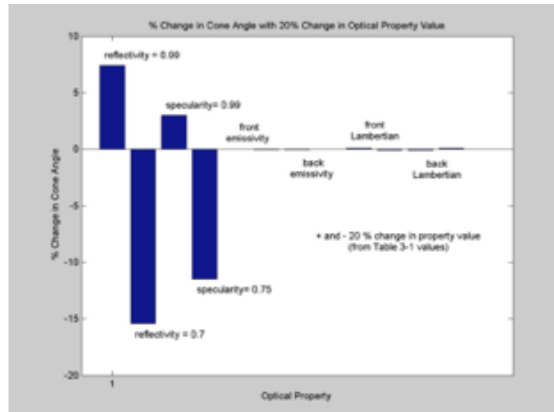

Fig. 8. Relative effects of optical properties on sail thrust direction

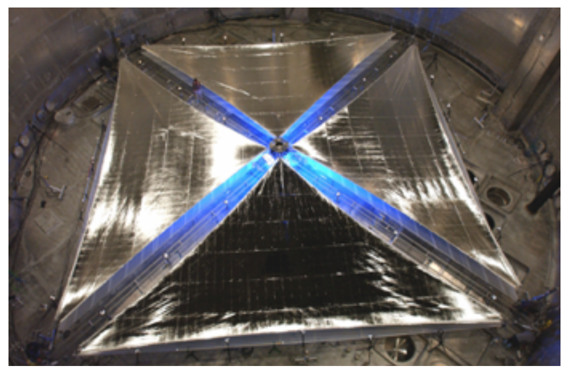

Fig. 9. Prototype "tensioned" sail

Fig. 10. Prototype "draped" sail

As can be seen, the tensioned sail has a flatter surface than the draped sail, which in addition to billow between the booms also shows "stripes" of material between the support wires between the booms that have their own billow. Both sails also have noticeable creases, wrinkles, and crinkles (Figures 11 and 12) mostly due to manufacturing (rip stops) and handling (folding, packaging and deploying). These shape properties also affect the magnitude and direction of the resulting total radiation pressure force generated by the surface.

Fig. 11. Wrinkles and creases

Fig. 12. Crinkles

In order to analyse the comparative difference in performance for such non-ideal sails, models were created for four representative sail types, as shown in Figure 13. The first is an "ideal" sail with a flat, perfectly reflecting surface. The second is a flat sail with non-ideal optical properties. The third model is a reasonably flat sail surface with billow between the booms (similar to Figure 9), and the fourth model is of a draped sail similar to Figure 10.

The sail (and sailcraft) properties used for each model are shown in Table 2. Note that total (sailcraft) mass, and total sail (material) area are the same for each model. Optical and shape properties for each model were derived from information gathered during the ISP developments.

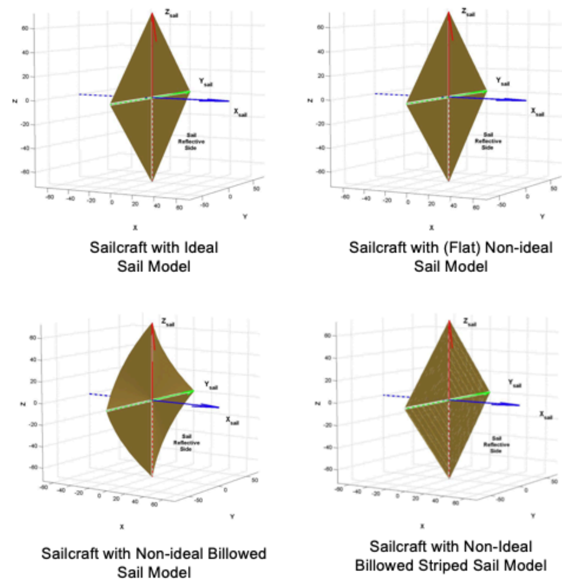

Fig. 13. Solar sail model types

Table 2. Solar sail model properties

	Ideal sail	Non-ideal (flat) sail	Realistic (billowed) sail	Realistic (striped) sail
m_{sc}	300 kg	300 kg	300 kg	300 kg
m_s	60 kg	60 kg	60 kg	60 kg
m_p	240 kg	240 kg	240 kg	240 kg
A_{sail}	10,000 m^2	10,000 m^2	10,000 m^2	10,000 m^2
Billow (θ_b)	0	0	10^o	10^o
Droop (θ_d)	0	0	5^o	5^o
t_r	0	0.02	0.002	0.02
a_b	0	0.1	0.08	0.12
r_f	1	0.88	0.918	0.86
s_{act}	1	0.94	0.978	0.55
ε_f	0	0.05	0.02	0.03
ε_b	0	0.55	0.269	0.4
B_f	2/3	0.79	0.79	0.89
B_b	2/3	0.55	0.55	0.65

These properties were input to a Solar Sail Module "toolbox" created by Princeton Satellite Systems (PSS) [3] developed for the ISP program. Each sail "quadrant" can be separately modelled and broken into a number of individual surface elements (Figure 14), for which each element radiation force can be calculated and summed together to determine overall sail force magnitude and direction. This can be done over a range of sun-incidence angles, and performance values displayed and plotted.

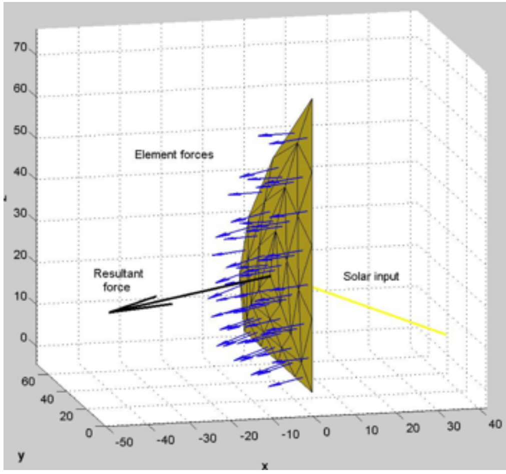

Fig. 14. Sail quadrant forces
(PSS Solar Sail Module)

4. Results

Table(s) 3 show the total thrust levels (for 0^{o} and 35^{o} cone angles) and sailcraft characteristic acceleration (0^{o} cone angle at 1 A.U.) for each sail model. As can be seen, incorporating more of the non-ideal characteristics of the sail results in a decrease in overall performance (as might be expected). Note that this indicates between a 10 and 20 percent decrease in performance depending on the combination of sail optical and shape properties of the sailcraft.

Table 3. Solar sail model performance

Thrust Level Comparison

	Ideal sail	Non-ideal (flat) sail	Realistic (billowed) sail	Realistic (striped) sail
0^{o} (N)	0.091	0.082	0.074	0.067
35^{o} (N)	0.063	0.056	0.053	0.048

Characteristic Acceleration Comparison

	Ideal sail	Non-ideal (flat) sail	Realistic (billowed) sail	Realistic (striped) sail
a_C (mm/s^2)	0.304	0.273	0.267	0.243
		-10.2%	-12.2%	-20.1%

This decrease in performance is also illustrated in Figure 15 which plots each sail model total force over sun-incidence angle. Figure 16 plots the change in cone angle with incidence angle to the sun. While it is theoretically possible to point an ideal solar sail (the "front" shiny side used for propulsion) up to 90^{o} off the sun-line, it can be seen that there is a maximum angle off the sun-line that the force vector (direction) can be pointed, and which is significantly impacted by sail shape.

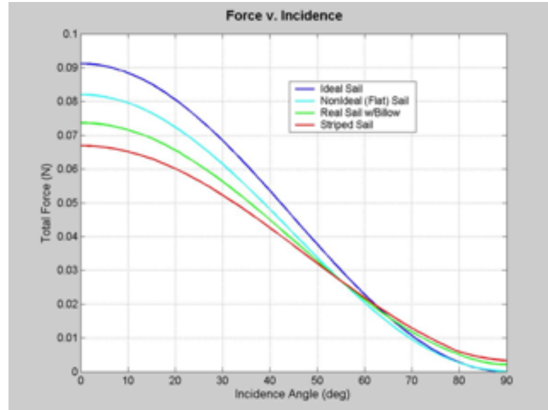

Fig. 15. Sail model force vs. sun-incidence angle

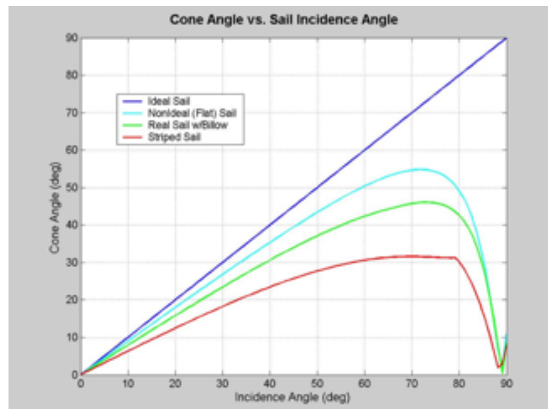

Fig. 16. Sail model cone angle vs. sun-incidence angle

5. Discussion

For a solar sail mission, attitude control is trajectory control is mission control – especially considering that under normal situations the sail will be continuously generating thrust. Mission trajectories, incorporating this persistent thrust and the cone angle limitations in direction of the thrust, must develop an associated sail attitude control (pointing) profile that will meet the objectives of the mission. This is challenging even for an ideal sail, and complicated even more for a non-ideal sail.

Two major points can be seen in the prior material. The first has to do with the inherent uncertainty in the magnitude and direction of the thrust force generated by the sail. Important sail properties, including optical and shape, are difficult to determine precisely during development and testing on the ground. An important component of this uncertainty is associated with the offset between the sailcraft center of mass (Cm) and center of pressure (Cp) generated by the sail forces. This can impact the stability and responsiveness of whatever attitude control system (ACS) approach that is implemented – many of which plan on using the same solar radiation pressure (SRP) forces and their own inherent uncertainties.

The second major point has to do with ensuring that these uncertainties are incorporated in the mission design. Development of mission trajectories must ensure that calculation of "optimal" flight paths and their associated sail pointing profiles include sufficient "margins" such that recovery from any underperformances do not require the sail to exceed its capabilities (thrust magnitude and/or direction). The resulting trajectory will provide information/requirements that can translate into sailcraft systems designs, such as ACS approach, on-board guidance and navigation (GN&C) design (position and attitude measurements) and the associated feedback (and frequency) to the control systems to meet the desired trajectory and mission objectives (attitude control is trajectory control is mission control).

Finally, it is urgent that a comprehensive solar sail demonstration mission be flown. Early missions such as Japan's IKAROS, NASA's NanoSail, and the Planetary Society's LightSail, demonstrated some important aspects of solar sailing, such as deployment and thrust generation, however none of these provided the kind of performance and operation necessary to validate the current models being used for solar sail mission (and sailcraft) design. A dedicated, fully capable and instrumented sailcraft could demonstrate not only thrust generation, but also positive control and trajectory performance as well as other important sailcraft operations information. This would provide actual sail performance that could be compared to the pre-flight models used for the mission design, and allow updates to allow better following mission design. Such a demonstration mission, the Advanced Composite Solar Sail System (ACS3) is currently being developed by NASA and scheduled for launch in the near future.

While these better models will allow better future, more complex solar sail mission (and sailcraft) design, there will still be inherent uncertainties associated with manufacturing and handling of the sail materials and components for each and every sailcraft developed. Because of this, even for identical "copies" of sailcraft, there is an obvious need for any solar sail mission to have a calibration campaign after deployment in space to compare to and adjust the models used for the mission planning. While not an integral part of the actual mission objectives, such a campaign will allow operational refinements of the mission to increase confidence of mission success.

6. Conclusions

Use of "ideal" sail models for solar sail mission concepts and proposals contain overly optimistic sail capabilities that do not sufficiently represent a configuration that would need to be developed to realize the mission. Use of more "realistic" solar sail models, addressing both thrust performance and sailcraft trajectory control, would ensure that concept feasibility and required developments and potential mission success are better reflected. Flying a dedicated and comprehensive solar sail demonstration mission would provide information needed to update current models and allow even better solar sail mission concept development and proposals for future missions.

References

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