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Light Sail Movement with Photon Energy; Solar Sail

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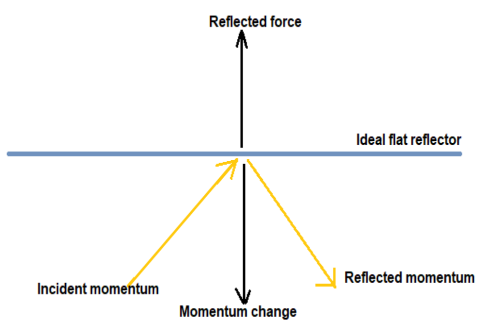
ABSTRACT:
The current technology needs to move on alternate energy due to lack of resources and environmental problems. Therefore, solar sails have become a major option for the current satellite missions. Solar sails work on renewable energy and have a long life time as they did not carry any fuel on board. The interest in developing the determined solar sail increased over recent years. The sail design was proposed in the 1970s but not implemented due to the lack of technology. In the early 2000s, the sails are launched into space by several space agencies. This study determines the different solar sail designs and their comparison to determine spin-stabilized sail as a desired one by the thermo-structural analysis. Also, the sail configuration and parameters, attitude controls, packing, and the active deployment demonstrator are determined.

Keywords*:* Solar sail, satellite, renewable energy, spin-stabilized, thermo-structural analysis, parameters and configuration, attitude controls, active deployment demonstrator.

INTRODUCTION:
Solar sails are light sails that move with the help of solar energy. It is a propulsion technology used for accelerating the satellite in the desired orbits. It works on the principle of Newton's third law. This technology is helpful for future missions as it works with the help of renewable energy and makes the satellite move to interplanetary orbits very quickly compared to the present technology. Solar sails are usually in different shapes, sizes, and different stabilizations. This study determined the disc spinning design in the desired packing and the deployment. It is more resistant to c_m and c_p offset and disturbance torques and gives continual centrifugal force. The non-rigid spinning sail is capable of performing fast attitude maneuvers than a standard rigid three-axis stabilized sail. This makes the satellite with this stabilization change its orbit and enter the interplanetary probe with the help of the solar thrust. In regards to stability, attitude dynamics to be obtained with the help of the

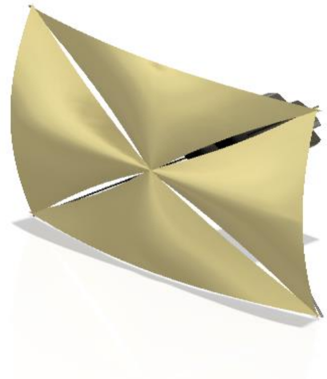


attitude control system.

DESIGNS:

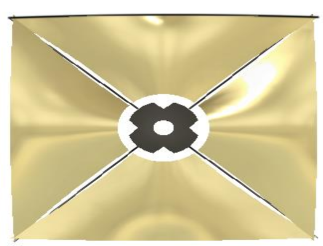
The six different sails are designed in Fusion 360.

Square Shaped Three-Axis Stabilized Sail*:*



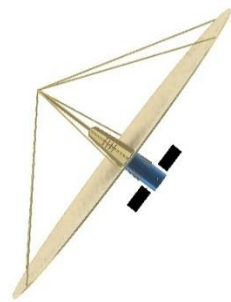
The sail in the shape of a square and looks like a kite, as shown in the figure. This uses a rigid structure to extend its material in the space that is supported by fixing the booms at the center of the sail so that collapsing will be prevented. Booms, Masts, and stays are used for giving stiffness to the sail. The three-axis stabilization supports the structure in all three dimensions, or axes, without spinning. The attitude was controlled by changing its Centre of mass location relative to its Centre of pressure location. This was achieved by placing a controlled boom with a tip-mounted mass or other techniques. Light sail-1, Light Sail-2, Deorbit sail, Gossamer-1, and Surrey Cube Sail come under this category. These sails used Launch vehicle upper stage attachment, Momentum wheels and, Magnetorquers for attitude control.

Square Shaped Spin Stabilized Sail:



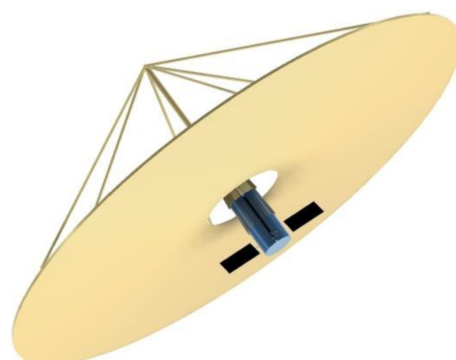
The sail is in the shape of a kite, but unlike the three-axis stabilized sail as shown in the figure, it rotates around its vertical axis. This sail spins continuously to assist it in maintaining a steady flight path. Attitude controls should be given to this type of sail also. IKAROS is the only sail of this type developed till now, and here, chemical thrusters and LCD panels were used for attitude control. .

Disc Shaped Three-Axis Stabilized Sail:



The figure shows that this is similar to the square-shaped three-axis stabilized sail, but here, the shape of the sail is disc instead of square. This type of sails has a stabilized satellite body. The disadvantage in this type of sail is that it should require stiff booms to make it immune to the Centre of mass and the Centre of pressure offsets. Inflate sail is an example of this type, and this sail used the Momentum wheel and magnetorquers for attitude control.

Disc Shaped Spin Stabilized Sail*:*

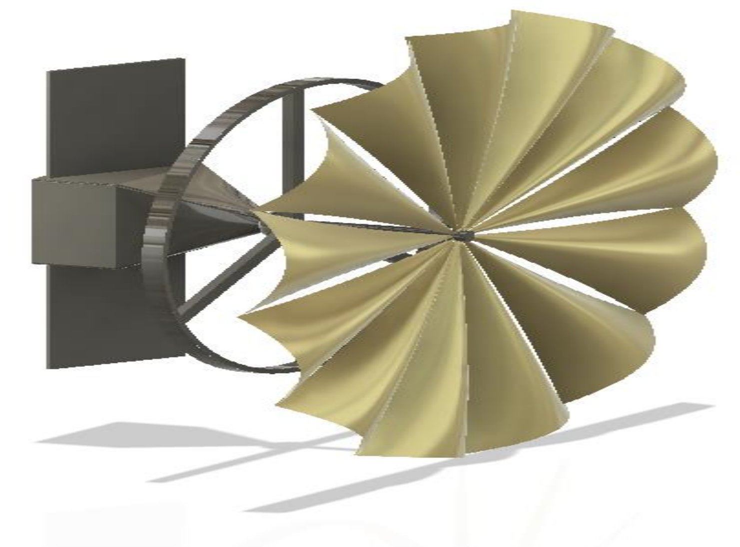


These are circles in shape, as shown in the figure. There exist some small gaps between sail masks that help in maximizing the amount of surface area. Usually, large spinning discs support by the lightweight tension lines and carry loads except at the center. These sails can be used to monitor cities in the Arctic Circle and also for future missions. The first sail launched on space Znamya was of this type, but it failed due to technical issues.

Polygonal Shaped Sail:

A Sail can be of any shape. A polygonal sail can also be used for solar sailing giving it either three-axis stabilization or spin stabilization. JAXA is designing sail in the shape of a cloverleaf. This type of sail has not been launched or developed till now. But this also can be considered based on the requirement.

Heliogyro:



Heliogyro sails are solar sails that are composed of several vanes or blades, as shown in the figure. While deploying, the vanes get rolled out and extend directly from the hub because of the spinning motion of the craft. These are very long. Due to that, it is more complex to manufacture this sail. Cosmos-1 and Illinois cube sail are heliogyro sails. This sail was proposed in the 1970s with the design proposed having 6 blades each of 15m wide and 7, 34,000 m long. Here the major advantage is the storage of blades and in-orbit deployment. The large blade dimensions of this sail cause dimensional effects.

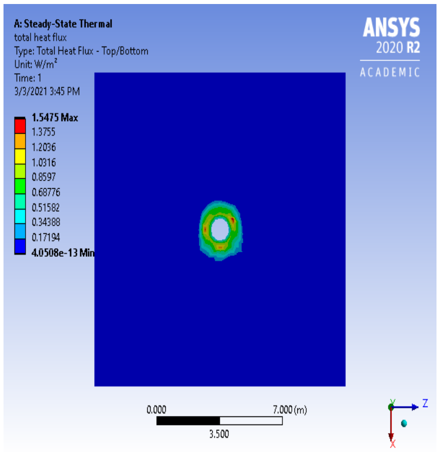
THERMO STRUCTURAL ANALYSIS: CHAPTER 4

Thermo structural analysis is one of the applications of the finite element method used to calculate the temperature disturbance caused within the sail design, with the help of the thermal inputs, outputs, and other thermal barriers in the sail.

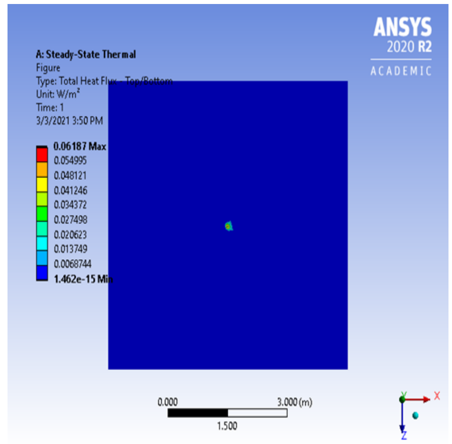
Analysis of Sails:

The analysis of six different sails was done, and the results are compared to each other. The sails used are disc-shaped sail with spin stabilization of sail area 175 m^2, three-axis stabilized disc sail of surface area 314 m^2, square sails of both spin-stabilized, and three-axis stabilized with a surface area of 195 m^2 and 36 m^2, respectively, 65 m^2 three-axis stabilized sail of hexagonal shape and heliogyro of 0.88 m^2. The Thermo structural analysis of these six different sails was performed in the Ansys workbench. The integrated modeling is adopted here, and the only part that shows simulation is the sail membrane. The material used for all these sails was aluminized mylar of thickness 0.005 mm. The input conditions given for the thermal analysis are radiation, temperature, the emissivity of 0.0044, heat flux, and other required conditions. Structural analysis is also performed, and the outputs obtained were compared for these six different sails in both structural and thermal cases where heat flux, thermal deformation, and maximum principal stress are determined.

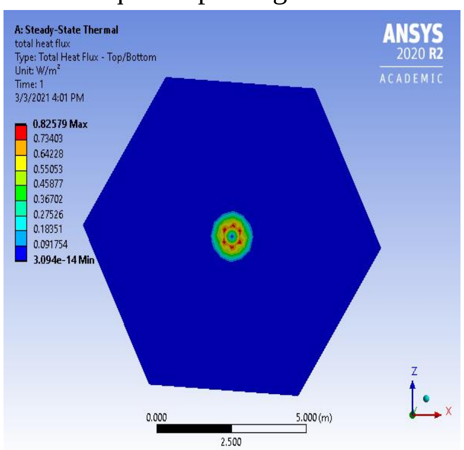
Heat Flux Analysis:



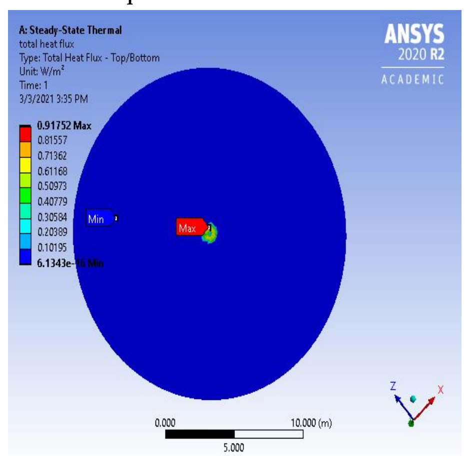
Heat Flux of Square Spinning Sail



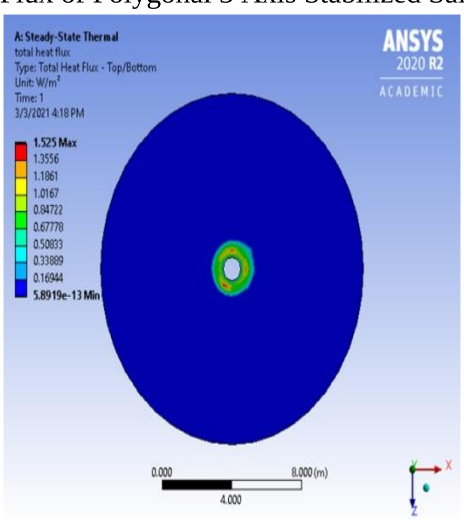
Heat Flux of Square 3 Axis Stabilized Sail



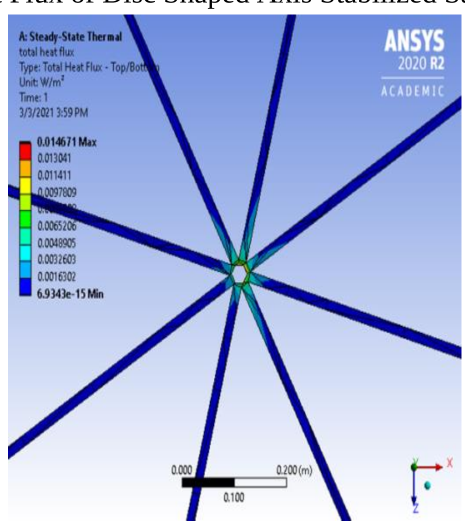
Heat Flux of Polygonal 3 Axis Stabilized Sail



Heat Flux of Disc Shaped Axis Stabilized Sail

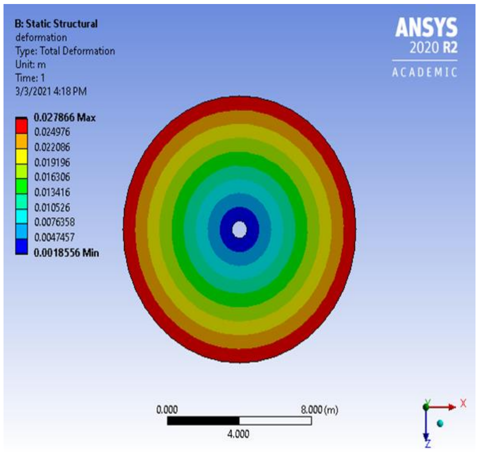


Heat Flux of Disc Spinning Sail

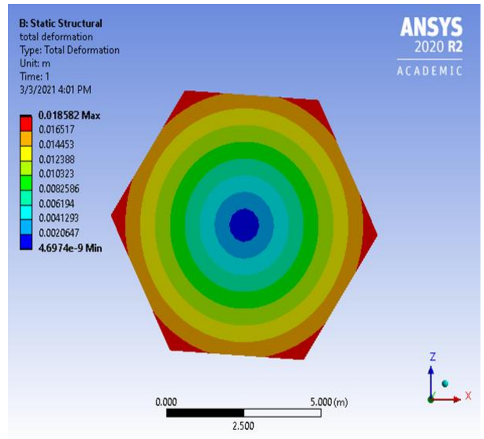


Heat Flux of Heliogyro Sail

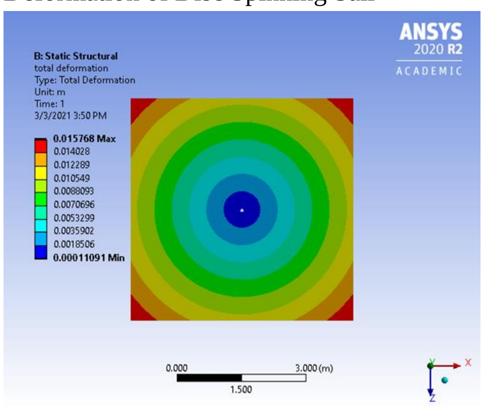
Deformation Analysis:



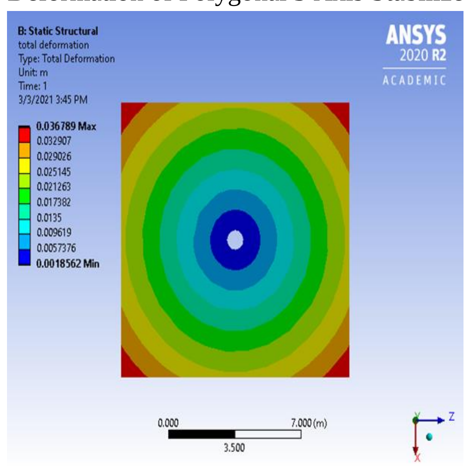
Deformation of Disc Spinning Sail



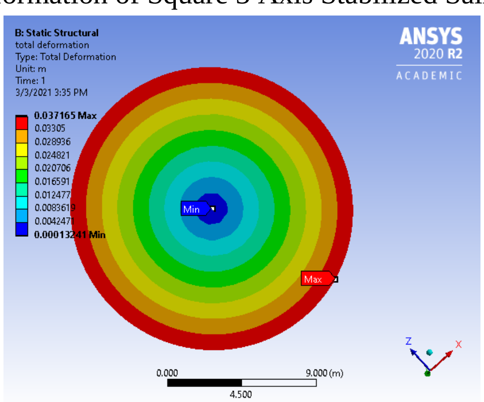
Deformation of Polygonal 3 Axis Stabilized Sail



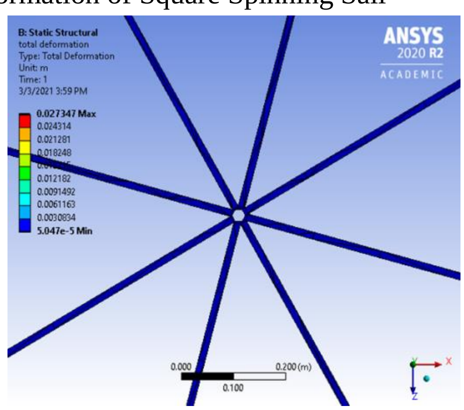
Deformation of Square 3 Axis Stabilized Sail



Deformation of Square Spinning Sail

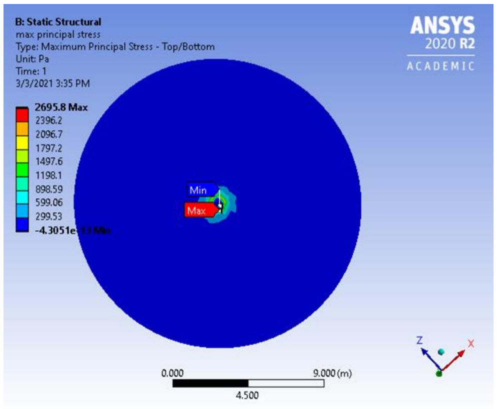


Deformation of Disc 3 Axis Stabilized Sail

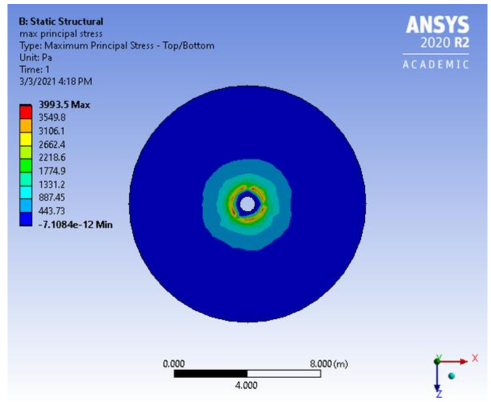


Deformation of Heliogyro Sail

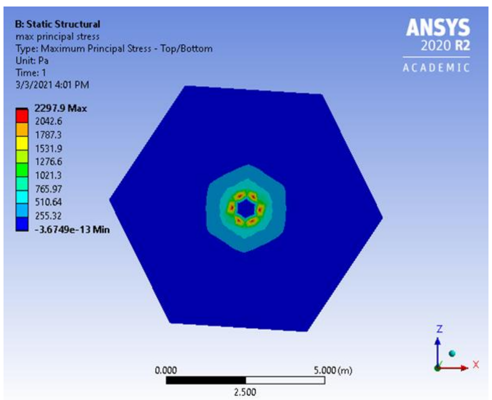
Maximum Principal Stress Analysis



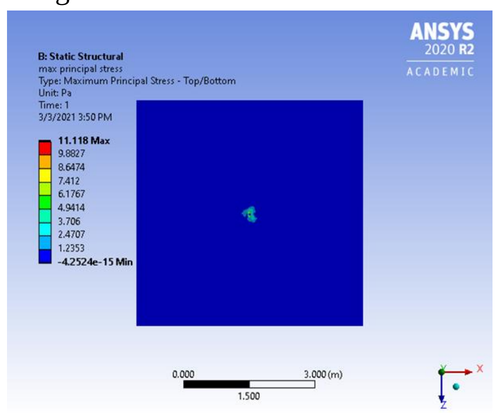
Max Principal Stress of Disc 3 Axis Stabilized Sail



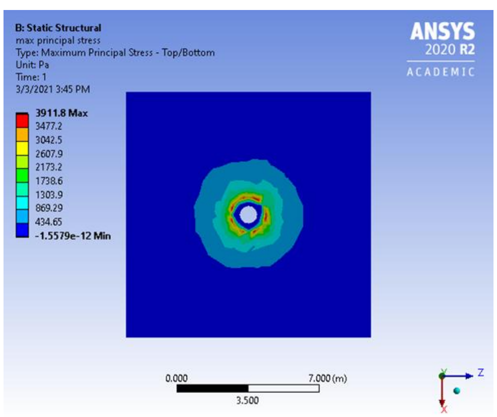
Max Principal Stress of Disc Spinning Sail



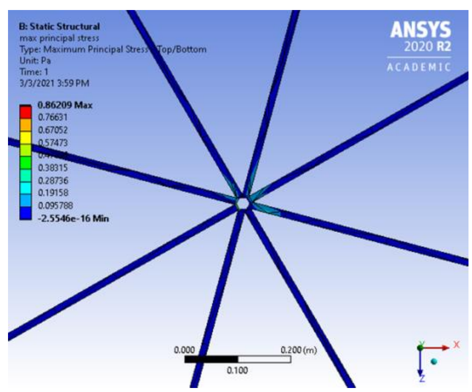
Max Principal Stress of Polygonal 3 Axis Stabilized Sail



Max Principal Stress of Square 3 Axis Stabilized Sail



Max Principal Stress of Square Spinning Sail



Max Principal Stress of Heliogyro Sail

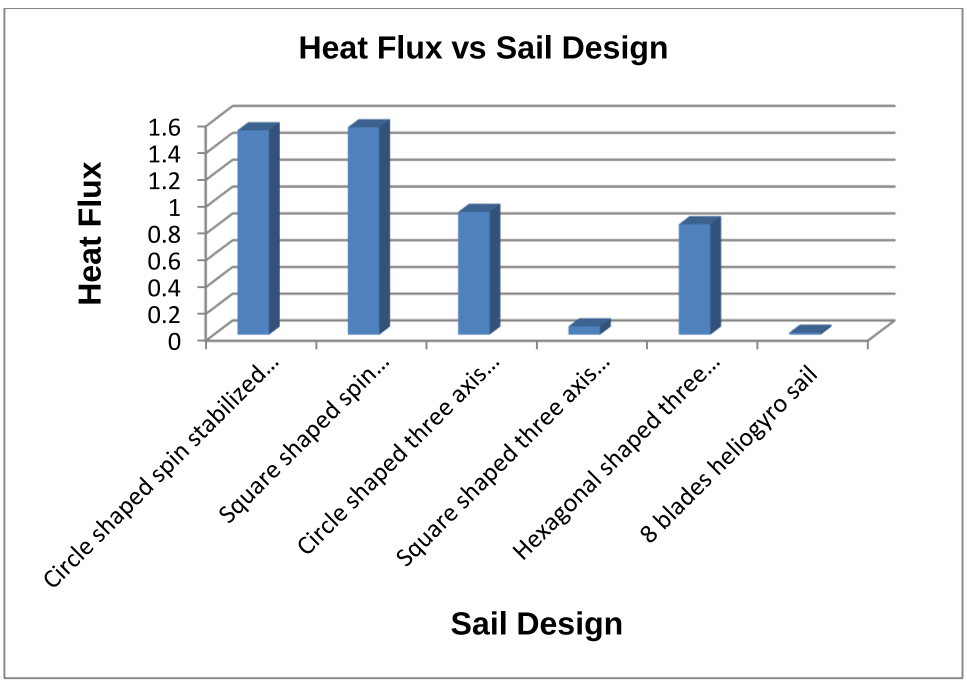
Comparison:

The sails were analyzed, and then these are compared to each other in the form of bar charts. The different sails with various shapes and stabilizations show the difference in their thermal and structural outputs.

Analysis Data Comparison

Types of solar sail	Surface area(m^2)	Maximum total heat flux(W/m^2)	Total deformation(m)	Maximum principal stress
Disc-shaped spin-stabilized sail	175.93	1.525	0.04204	590.81
Square shaped spin-stabilized sail	195.21	1.5475	0.014312	638.48
Disc-shaped 3-axis stabilized sail	314.16	0.91752	0.0285	47.197
Square shaped 3-axis stabilized sail	36	0.06187	0.0090941	0.064467
Hexagonal shaped 3-axis stabilized sail	64.952	0.82579	0.011657	128.83
8 blades heliogyro sail	0.88118	0.014671	0.0213701	0.0070576

Comparison of Heat flux:



From Figure, it was clearly stated that the spin-stabilized sails possess a large heat flux compared to the other sail types. By the Einstein's relation

$$p = E/c$$

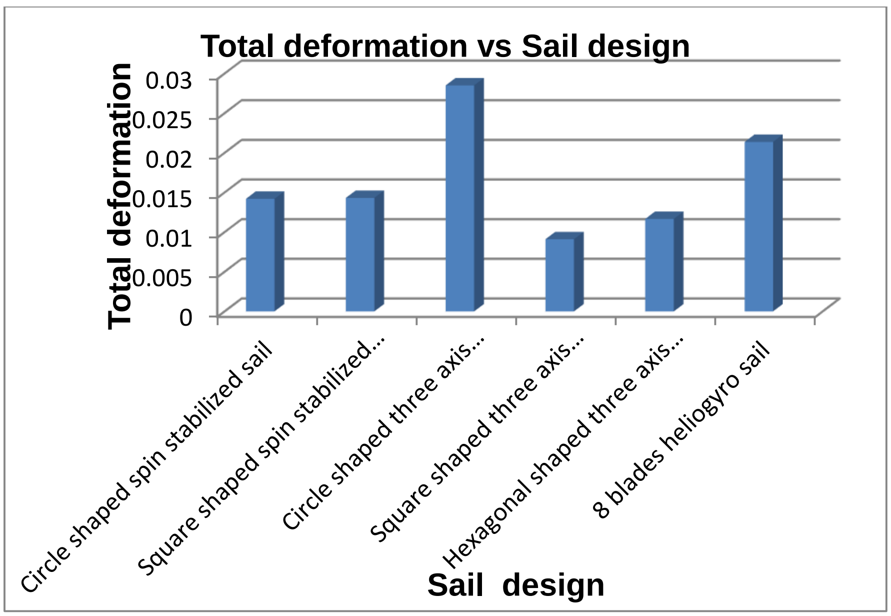
$$p \propto E$$

Where p is the momentum of a photon, E is the heat flux energy, and c is the speed of light. Therefore, large heat flux produces more momentum. The incident momentum is proportional to the reflected momentum, which helps in the sail movement. The spin-stabilized sails have an average heat flux of 1.5 W/m^2, whereas three axes stabilized possess an average of less than 0.6 W/m^2. Hence the spin-stabilized sail is preferred.

Comparison of Total Deformation (m):

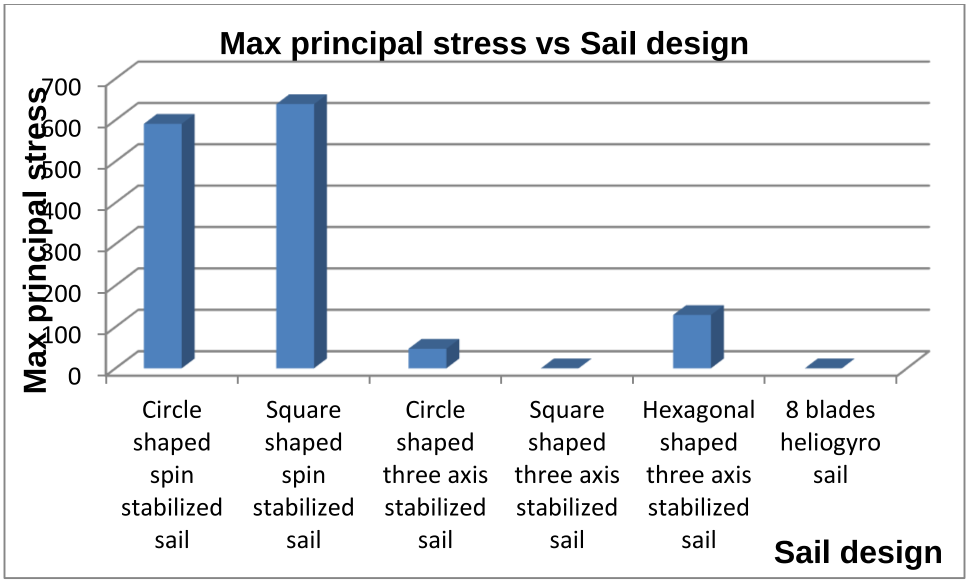
The small deformation is common on any solar sail structure because of the solar pressure. The structural deformation affects the geometry parameters and acceleration of the sail. The deformation should be smaller as the torque devastating would be smaller, and the controlling ability will be easy. Therefore, deformation is made smaller, and while designing the sail, deformation corrections are made. This is done by correcting or changing the geometry, and then deriving the deformation by the Finite element analysis. To get an accurate model, a sail

with small deformation is preferred



The figure shows the total deformation of different sails. The total deformation to the surface area of the solar sail is determined, and the sail with the lowest value is considered as the desired sail. The disc spinning sail has a ratio of 0.000079, and the square spinning sail is 0.000075. The three-axis stabilized disc sail, square, and polygonal has a ratio of 0.000095, 0.000275, and 0.000172, correspondingly. Heliogyro has a deformation ratio of 0.02272. Considering all those values spinning sail is most preferred.

Comparison of Maximum Principal Stress:



Maximum principal stress formula is given as

$$\sigma 1{,}2 = \sqrt{\left[\frac{\sigma_x + \sigma_y}{2}\right]^2 + \tau_{xy}\text{^}2}$$

Where, σ x = shear stress (stress = force/area) σy = tensile stress

τ = Torque

Hence the maximum stress is proportional to the maximum force that can be exerted on the sail surface. As shown in Figure, the spin-stabilized sails possess more stress compared to other types. Hence these are preferred.

Solar Sail Configuration and Parameters*:*

The sail parameters are calculated for the spin-stabilized disc sail made from aluminized mylar sheet. Generally, the solar sail is affected by four main parameters those are sail loading, lightness number, characteristic acceleration at 1 AU from the sun, and angular rate of sail. Since it is the spin-stabilized sail, the centrifugal force formed prevents the Centre of pressure and Centre of mass offset. The centrifugal force is calculated by considering the IKAROS sail as it was the spin-stabilized sail like the designing sail. The mass of a single tip was 500 g, and the nominal angular rate at the end was considered as 1 rpm. The radius of the sail was 10 m. The centrifugal force generated was

$$F_c = mr\,\omega^2 \qquad [\ \omega = (2*\pi*RPM)/60]$$

$$F_c = 0.5*7*0.105*0.105$$

$$F_c = 0.055125 \text{ N}$$

The satellite designing was considered to have low tip mass than IKAROS, with 10 g and a radius is 7.5 m. Therefore, to have the same centrifugal force as IKAROS, the successful sail, placed in orbit. The sail should possess an angular rate of

$$\omega_n = (F_c/(m*r))*0.5$$

$$\omega_n = 0.85732 \text{ rad/s}$$

$$\omega_n = 8.191 \text{ rpm} = 8 \text{ rpm}$$

The sail design is made of aluminized mylar material. This material is of thickness 0.0045 mm, and the density is 1.39 g/cm^3. The mass of sail is 1095 g and the satellite used is a 6 U satellite with an overall mass of 12 kg. The sail has a surface area of 175 m^2. The sail loading of the designed sail is

$$\sigma = \text{mass/ sail surface area}$$

$$\sigma = 12000 / 1750000$$

$$\sigma = 0.0006857 \text{ g/cm}^2$$

$$\sigma = 68.57 \text{ g/m}^2$$

Assuming an efficiency of 90% of radiation pressure at a distance of 1 AU from the sun, the solar radiation pressure is 8.17 μ N/m^2 of radiation pressure. The characteristic acceleration is given by

$$a_c = 8.17/ \text{ sail loading}$$

$$a_c = 0.12 \text{ mm/s}^2$$

The lightness number is independent of the distance from the sun. Gravity and light pressure is the inverse square of the distance from the sun. This number is defined as the number of orbital maneuvers possible for the proposed sail design. Lightness number is the maximum acceleration divided by the sun's local gravity. For a sail of 175 m^2 surface area, the lightness number is approximately

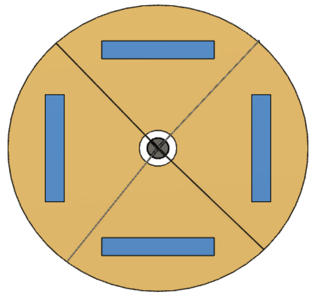
$$\lambda = a_c/ 5.93$$

$$\lambda = 0.021$$

Compared to the other sails, IKAROS produces an acceleration of 0.01 mm/s2, and the proposed sail was able to produce more characteristic acceleration.

Attitude Controls:

Attitude controls of the sail are determined as the steering of the sail. The two major factors that are affecting the speed and control of the sail are structural analysis of the sail and the torque abilities of its attitude control system. For the non-rigid elements, the oscillations lead to the change in the distribution of mass, which further changes the moment of inertia, causing the sail to change the attitude control and rotational dynamics of the sail. Even though, Sail is designed in such a manner that both the c_m and c_g of sail coincides after the sail gets fully deployed. The deployment creates an offset distance between c_m and c_g. Therefore, due to the offset, it is necessary to maintain the proper attitude control to the sail to maintain the sail constantly in a certain orbit. Attitude control of sail can be achieved in different ways.

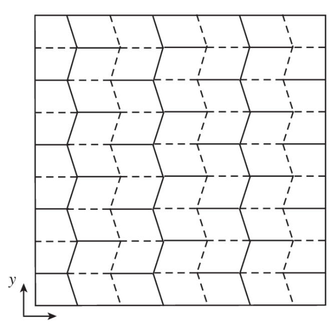


Generally, for the non-rigid sails, the only option available is to move the c_p to obtain stability to the sail. However, the c_m is not supposed to move as this also leads to the changing of the spin axis and even the spin plane. Non-rigid sails also possess control with the help of passive attitude stability.
The attitude controlling for the disc spinning sail designed here is obtained by the reflective devices as shown in the figure. The reflective devices are of different types including, coating the sail membranes, installing LCD panels, or using reflective panels. The attitude controls are acquired by possessing the change in control torque of the sail. The reflective LCD panels are placed on all four sides of the sail with the automatic on/off technique, which helps in the transmissivity of the constant torques and provides the required attitude control to the sail. These devices produce the required transmissivity changes by changing the voltage applied.

Packing:

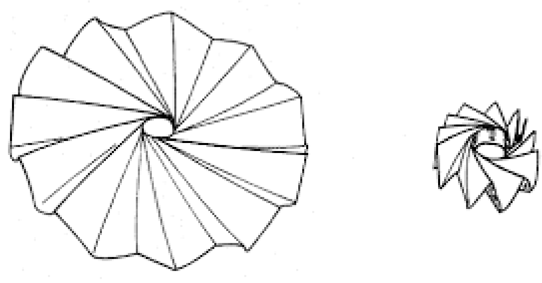
A Solar sail cannot be directly taken to space by the launch vehicle because of its size. Usually, a large flexible sail membrane is used as a mirror that reflects the photons. Therefore, the sail has to be packed into a reasonable volume so that it fits into the launch vehicle. Packing is the most challenging in designing the sail, while deploying it should not cause any damage to the thin sail membrane.

There are numerous ways in which the sail is packed in a certain body to fit inside the launch vehicle. This packing is usually made depending on the shape, type of the sail, and also the materials used for the sail manufacturing. For the design, a disc-shaped spin stabilization sail has more flexible wire booms which are easily packed, and the technique used here is folding the membrane around the satellite and fitting it in a cube-shaped structure so that the large sail will be fitted into a smaller volume.



Miura-Ori Folding Technique

Miura-Ori technique is the well-known folding. It is a map folding technique by folding in one set of parallel fold lines, as shown in the figure.



Guest and Pellegrino Folding Technique

This folding is mainly forming a solid cylinder folding, as shown in the figure, which can be used in the circular spinning sails. These mountain folds are shown as solid folds, dotted folds, etc.

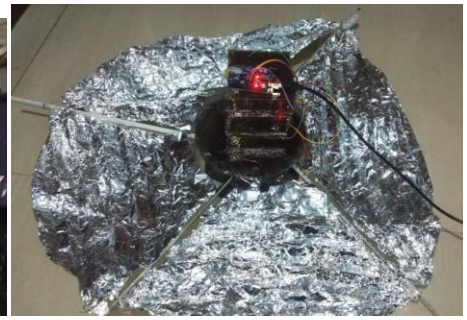
This Miura-Ori and Guest &Pellegrino folding were the packing techniques used to pack the disc spinning sail in a certain volume.

Deployment Mechanism:

The deployment mechanism in the disc spinning sail is also important to consider in designing a sail. Deployment dynamics are needed to be understood in designing a successful sail. The sail is made to deploy once it is fixed in the desired orbit. The deployment is easier for a spiral folded sail by some origami techniques compared to the other types of folded sails. These spiral folded sails will be deployed smoothly within seconds such that they get unreeled more quickly but experiences some disturbances due to the rapid unfolding, these vibrational disturbances will be reduced by installing damped materials that are attached to the damped phase to reduce unwanted plane vibrations. The active deployment can be used for the disc spinning sail.

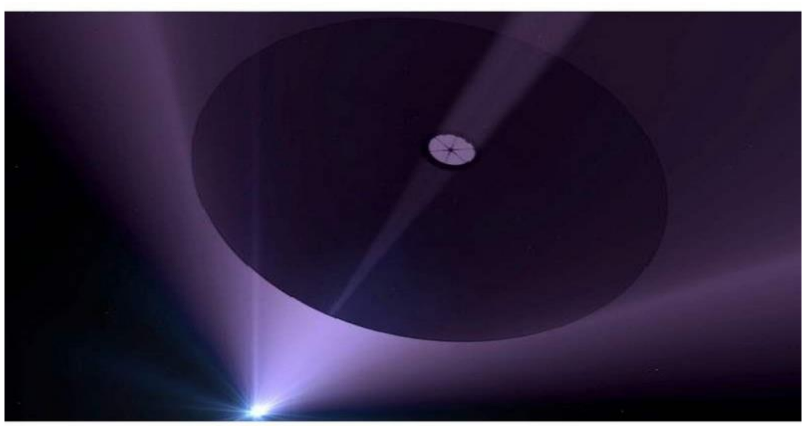
In the active deployment mechanism, the deployment component will work on a relative rotating mechanism. The solar sail is deployed with the help of an electrical motor. A pulley is attached to the motor, which helps to compact the wire booms and to deploy. The Electrical stepper motor is programmed, and sensors are attached to provide the feedback of the system. The motor is considered and rated by the maximum rotations or total rotations.

The wireless module contains its battery power source is placed on the deployment mechanism. The deployment will be completed in the given certain time with the battery usage. There will be no effect on the mechanical design, which deploys by a period. Here, the length of the booms increases steadily because of the pulley method used. Then, the sail membrane folded by Miuro-Ori and Guest and Pellegrino techniques will be released. So, the sail will be deployed completely. Active deployment is a less complex and low expensive mechanism.

Conclusion:

Solar sails can deploy huge sail membranes in space, and their attitude is controlled to face the membrane surface to the sun. The sail cannot be taken into space directly, and this needs to be fitted in a small volume. Therefore, the sail membrane used here is very flexible, which helps to carry large sails to space. The large sails can also be accelerated to other planet orbits. Renewable energy is used by this sail instead of other fuel energy, which will be helpful for future missions as there is no need for external energies and as there is no need of carrying any kind of fuel and other energy sources, the lifespan of the sail is large. Solar energy needs not to be converted from DC to AC, unlike the other solar devices, which make the work cheaper and easier. Due to this, there will be no pollution and environmental problems. The attitude control used here is made with solar panels, which do not require any kind of external energy and uses only the photon energy from the sun. The booms used are the wire booms which also useful for several missions in the future as these are easily deployable than other supports. The spinning sails usually produce more acceleration that helps in interplanetary space exploration. This solar sail can also be propelled with laser energy, as shown in the figure. So that the sail will be directed towards the desired direction and makes the sail reach other planets very quickly than the recent technology that is using now. There are numerous missions planned in the near future. With photon energy, it is possible to reach the mars in 3 days however recent technology is taking around 5 months. Similarly, it is possible for interplanetary exploration. This work provides a design that can fit in a small volume and producing more acceleration which is essential in future missions.



Sail Movement with Laser Propulsion

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