

LIGHT SAIL MOVEMENT WITH PHOTON ENERGY; SOLAR SAIL

Submitted in partial fulfillment of the requirements for the award of

Bachelor of Engineering degree in
Aeronautical Engineering

By

R.N.L. CHITTITALLI (Reg. No. 37260009)

S.T.V.S. VAMSI (Reg. No. 36260052)



**DEPARTMENT OF AERONAUTICAL ENGINEERING
SCHOOL OF MECHANICAL ENGINEERING**

SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with grade “A” by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119

APRIL 2020

DEPARTMENT OF AERONAUTICAL ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work R.N.L. Chittitali (Reg. No. 37260009), S.T.V.S.Vamsi (Reg. No. 37260052) who has done the project work as a team who carried out the project entitled “**LIGHT SAIL MOVEMENT WITH PHOTON ENERGY; SOLAR SAIL**” under our supervision from September 2020 to March 2021.

Internal Guide

Dr. MANIGANDAN SEKAR M.E., P.D.,

Head of the Department

Dr. BOOMA DEVI M.E., Ph.D.,

Submitted for Viva voce Examination held on 17/04/2021

Internal Examiner

External Examiner

DECLARATION

I R.N.L.Chittitali (Reg.No. 37260009) hereby declare that the Project Report entitled "**LIGHT SAIL MOVEMENT WITH PHOTON ENERGY; SOLAR SAIL**" done by me under the guidance of **Dr. MANIGANDAN SEKAR M.E., Ph.D.**, is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in Aeronautical Engineering.



DATE: 17/04/2021

SIGNATURE OF THE CANDIDATE

PLACE: Chennai

ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to the Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

I convey my sincere thanks to **Dr. S. Prakash, M.E., Ph.D.**, Dean, School of Mechanical Engineering, and **Dr. Booma Devi M.E., Ph.D.**, Head of the Department, Dept. of Aeronautical Engineering for providing me necessary support and details at the right time during the progressive reviews.

I would like to express my sincere and deep sense of gratitude to my Project Guide **Dr. Manigandan Sekar M.E., Ph.D.**, for his valuable guidance, suggestions, and constant encouragement that paved way for the successful completion of my project work.

I also express my thanks to all Teaching and Non-teaching staff members of the Department of Aeronautical Engineering who were helpful in many ways for the completion of the project.

ABSTRACT

Solar sails have become a major option for the current satellite missions. The interest in developing the solar sail has been increased over recent years. Even though the sail design is proposed the 1970s, due to the lack of technology, it is not implemented. In the early 2000s, the sails are launched into space by several space agencies but many missions related to solar sail are failed. The major causes are a failure in deployment mechanism and another issues regarding solar sail is its size. A large sail membrane is required for solar sail and it is difficult to carry a sail of that size to transport to space. Different packing techniques also play a major role in sail designing. Different types of solar sail designs, as well as the packing technique, have been discussed. The advantages of the spin-stabilized solar sail over the three-axis stabilized are also stated. This study states the spin-stabilized sail's design, attitude controls, attitude and orbital dynamics, a packing technique which help in carrying huge sails into space, thermo-structural analysis of different solar sail designs and their deformation, deployment mechanism by building a disc-shaped sail deployment demonstrator using active deployment method that makes use of alternate current for deploying. Majorly focuses on the circle-shaped spin-stabilized sail as it would be easier to deploy. Spin stabilized sail is able to perform fast maneuvers and generates constant centrifugal force, unlike the three-axis stabilized sail. This helps in reducing sail billowing so that wire booms are used. Current challenges in this aspect are identified. The advantages over other sails and future implications have been stated.

Keywords: Solar sail, deployment mechanism, membrane, packing techniques, spin-stabilized, three-axis stabilized, attitude controls, orbital dynamics, thermo-structural analysis, active deployment, centrifugal force, sail billowing, wire booms.

TABLE OF CONTENTS

CHAPTER No.	TITLE	PAGE No.
	ABSTRACT	V
	TABLE OF CONTENTS	Vi
	LIST OF FIGURES	X
	LIST OF TABLES	Xii
	LIST OF SYMBOLS AND ABBREVIATIONS	Xiii
1	INTRODUCTION	1
1.1	Solar Sails	1
1.2	Working of Sail	2
1.3	History	2
	1.3.1 <i>Znamya 2</i>	3
	1.3.2 <i>Znamya 2.5</i>	3
	1.3.3 <i>Cosmos 1</i>	3
	1.3.4 <i>IKAROS</i>	3
	1.3.5 <i>Nanosail- D and Nanosail-D2</i>	3
	1.3.6 <i>Deorbit sail</i>	4
	1.3.7 <i>Light sail projects</i>	4
	1.3.8 <i>Projects in development</i>	4
1.4	Novelty of work	5

CHAPTER No.	TITLE	PAGE No.
3	SAIL DESIGN	19
3.1	Methodology Chart	19
3.2	Design	20
3.2.1	<i>Square Shaped Three-Axis Stabilized Sail</i>	21
3.2.2	<i>Square Shaped Spin Stabilized Sail</i>	22
3.2.3	<i>Disc Shaped Three-Axis Stabilized Sail</i>	23
3.2.4	<i>Disc Shaped Spin Stabilized Sail</i>	23
3.2.5	<i>Polygonal Shaped Sail</i>	24
3.2.6	<i>Heliogyro</i>	24
3.3	Solar Sail Configuration	24
3.3.1	<i>Disc Spinning Sail</i>	24
3.3.2	<i>Sail Satellite Structure</i>	25
3.3.3	<i>Parameters</i>	26
3.4	Attitude Controls	27
4	THERMO STRUCTURAL ANALYSIS	30
4.1	Analysis of Sails	30
4.1.1	<i>Heat Flux Analysis</i>	30
4.1.2	<i>Total Deformation Analysis</i>	31
4.1.3	<i>Maximum Principal Elastic Strain Analysis</i>	32

4.1.4	<i>Maximum Principal Stress Analysis</i>	34
-------	--	----

CHAPTER No.	TITLE	PAGE No.
4.2	Comparison Data	35
4.2.1	<i>Comparison of Heat Flux</i>	35
4.2.2	<i>Comparison of Total Deformation</i>	36
4.2.3	<i>Comparison of Maximum Principal Stress</i>	37
4.2.4	<i>Comparison of Maximum Principal Elastic Strain</i>	38
4.3	Sail Deformation	39
4.3.1	<i>Solar Radiation Pressure Force</i>	39
4.3.2	<i>Billowing and Wrinkling of Sail</i>	41
5	ATTITUDE AND ORBITAL DYNAMICS	43
5.1	Attitude Dynamics	43
5.1.1	<i>Newton-Euler Equations</i>	43
5.1.2	<i>Moment of Inertia</i>	44
5.1.3	<i>Disturbance Torques</i>	46
5.2	Orbital Analysis	47
5.2.1	<i>Orbits And Trajectories</i>	48
5.2.2	<i>Sun-Centered Orbits</i>	49
6	DEPLOYMENT MECHANISM	51
6.1	Active Deployment Mechanism	53
6.2	Packing	53

6.3	Deployment Experiment	55
-----	------------------------------	----

CHAPTER No.	TITLE	PAGE No.
	6.3.1 <i>Experimental Set-Up</i>	56
	6.3.2 <i>Outcome</i>	57
7	CONCLUSION	59
7.1	Design and Deployment Evaluation	59
7.2	Advantages over Other Sails	60
7.3	Future Implications	60
	REFERENCES	62

LIST OF FIGURES

FIGURE No.	TITLE	PAGE No.
1.1	<i>The Principle of Solar Sailing</i>	1
3.1	<i>Methodology Chart</i>	19
3.2	<i>Square Shaped 3 Axis Stabilized Sail</i>	21
3.3	<i>Square Shaped Spin Stabilized Sail</i>	22
3.4	<i>Disc Shaped 3 Axis Stabilized Sail</i>	23
3.5	<i>Disc Shaped Spin Stabilized Sail</i>	23
3.6	<i>Heliogyro Sail</i>	24
3.7	<i>Disc Spinning Sail</i>	25
3.8	<i>6U Cube Sat</i>	25
3.9	<i>Attitude Controlling of Sail</i>	28
4.1	<i>Heat Flux of Square Spinning Sail</i>	31
4.2	<i>Heat Flux of Square 3 Axis Stabilized Sail</i>	31
4.3	<i>Heat Flux of Polygonal 3 Axis Stabilized Sail</i>	31
4.4	<i>Heat Flux of Disc Shaped 3 Axis Stabilized Sail</i>	31
4.5	<i>Heat Flux of Disc Spinning Sail</i>	31
4.6	<i>Heat Flux of Heliogyro Sail</i>	31
4.7	<i>Deformation of Disc Spinning Sail</i>	32
4.8	<i>Deformation of Polygonal 3 Axis Stabilized Sail</i>	32

4.9	<i>Deformation of Square 3 Axis Stabilized Sail</i>	32
4.10	<i>Deformation of Square Spinning Sail</i>	32
4.11	<i>Deformation of Disc 3 Axis Stabilized Sail</i>	32
4.12	<i>Deformation of Heliogyro Sail</i>	32
4.13	<i>Max Principal Elastic Strain of Heliogyro Sail</i>	33
4.14	<i>Max Principal Elastic Strain of Square Spinning Sail</i>	33
4.15	<i>Max Principal Elastic Strain of Square 3 Axis Stabilized Sail</i>	33
4.16	<i>Max Principal Elastic Strain of Polygonal 3 Axis Stabilized Sail</i>	33
4.17	<i>Max Principal Elastic Strain of Disc Spinning Sail</i>	33
4.18	<i>Max Principal Elastic Strain of Disc 3 Axis Stabilized Sail</i>	33
4.19	<i>Max Principal Stress of Disc 3 Axis Stabilized Sail</i>	34
4.20	<i>Max Principal Stress of Disc Spinning Sail</i>	34
4.21	<i>Max Principal Stress of Polygonal 3 Axis Stabilized Sail</i>	34
4.22	<i>Max Principal Stress of Square 3 Axis Stabilized Sail</i>	34
4.23	<i>Max Principal Stress of Square Spinning Sail</i>	34
4.24	<i>Max Principal Stress of Heliogyro Sail</i>	34
4.25	<i>Comparison of Heat Flux</i>	36
4.26	<i>Comparison of Total Deformation</i>	37
4.27	<i>Comparison of Maximum Principal Stress</i>	38
4.28	<i>Comparison of Maximum Principal Elastic Strain</i>	39
4.29	<i>Solar Radiation Pressure</i>	40
5.1	<i>Attitude Dynamics of Sail</i>	43

5.2	<i>Cross-Coupling Dynamics</i>	46
5.3	<i>Sun-Centered Orbits</i>	49
6.1	<i>Deployment Mechanism</i>	51
6.2	<i>Miura-Ori Technique</i>	55
6.3	<i>Guest and Pellegrino Folding Technique</i>	55
6.4	<i>Deployment at 0 Sec</i>	57
6.5	<i>Deployment at 10 Sec</i>	57
6.6	<i>Deployment at 28 Sec</i>	57
6.7	<i>Deployment at 50 Sec</i>	57
6.8	<i>Deployment at 90 Sec</i>	57
7.1	<i>Sail Movement with Laser Propulsion</i>	61

LIST OF TABLES

TABLE No.	TITLE	PAGE No.
4.1	Analysis Data Comparison	35

LIST OF SYMBOLS AND ABBREVIATIONS

σ	Sail loading (g/m^2)
F_c	Centrifugal Force(N)
ω	Angular rate (rad/s)
a_c	Characteristic acceleration(mm/s^2)
Λ	Lightness number
σ_x	Shear stress (N/m^2)
σ_y	Tensile stress(N/m^2)
τ	Torque (W.m^2)
F_r	The Pressure of Incident Solar Photon (W)
e_r	Projected area (m^2)
F'_r	Reflected photons
F_{srp}	Total Solar Radiation Pressure(N)
F_{total}	Total Force(N)
M	A Moment on sail surface
μ	Billowed coefficient
Z	The function of wrinkled surface
w_n	End nominal angular rate(rad/s)
N	External Torque (W.m^2)
F_t	Tangential Thrust Force(N)
F_n	Normal Thrust Force(N)

F_s	Total Solar Thrust Force(N)
F_d	Drag Force(N)
N_d	Total Disturbance Torque due to the Drag Force (W.m ²)
N_s	Disturbance Torque due to Solar Thrust (W.m ²)
P	Solar Radiation Pressure (W/m ²)
P_s	Solar Radiation Pressure at a distance of 1AU from sun
m_{ss}	mass of sail surface(kg)
m_{st}	mass of sail booms(kg)
m_{sail}	mass of sail(kg)
m	mass of single tip(kg)
R	radius of sail(m)
r_{earth}	The radius of orbit of earth(m)
r_o	Reflection parameter
r_d	Local atmospheric density
v_{rel}	Relative velocity(m/s)
v_b	Escape velocity(m/s)
σ_t	Tangential coefficient
σ_n	Normal coefficient
P	Momentum of photon(kg.m/s)
E	Heat flux(W/m ²)
C	Speed of light(m/s)
β	The angle between light array and membrane

ϵ	The angle between normal sail surface and incident photons
M_i	The moment on surface ($W.m^2$)
M	Total moment ($W.m^2$)
$P(x, y)$	Function of billowed sail
$W(x, y)$	Function of wrinkled sail
$Q(x, y)$	Function of deformation
H	Angular momentum ($kg.m^2/s$)
H_b	Angular momentum of sail body ($kg.m^2/s$)
H_s	Angular momentum of satellite($kg.m^2/s$)
H_c	Angular momentum of the counter system($kg.m^2/s$)
I	Moment of Inertia($kg.m^2$)
I_b	Moment of inertia of sail($kg.m^2$)
I_s	Moment of inertia of satellite($kg.m^2$)
I_c	Moment of inertia of counter system($kg.m^2$)
ω_i	Angular rate between the inertial frame and the satellite (rad/s)
C_m	Centre of mass
C_p	Centre of pressure
C_g	Centre of gravity
N_g	Gravity gradient torque ($W.m^2$)

CHAPTER 1

INTRODUCTION

1.1 Solar Sails:

Solar sails are light sails that move with the help of solar energy. This is a propulsion technology used for moving the satellite in the desired orbits. It works on the principle of Newton's third law. Usually, solar sails are placed in orbits nearer to the sun such as L1 orbit. This technology is useful for future missions as it works with the help of renewable energy. This technology 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. Currently, rigid and non-rigid sails are present. In this study, the disc design in the desired size of packing and deployment is determined.

Consequently, spin stabilization and three-axis stabilization have existed. The spin-stabilized sail is easily deployable. This sail is more resistant to c_m and c_p offset and disturbance torques. It 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. The merits of the spinning sail design surpass the three-axis stabilized sail design. For getting stability to the sail, attitude dynamics should be achieved with the help of the attitude control system.

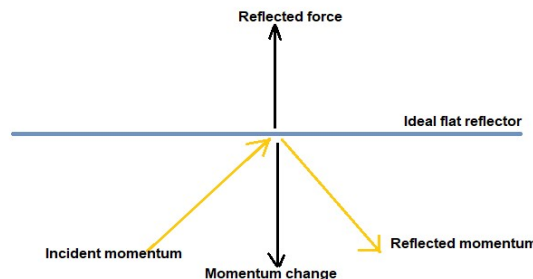


Fig 1.1: Principle of Solar Sailing

1.2 Working of Sail:

Solar sailing is a way of propelling a spacecraft by the radiation pressure. As shown in fig 1.1, solar sails are usually large mirror-like structures that reflect the photons from solar energy, helping the sail to move forward in the orbit. Solar sailing is a way of propelling a spacecraft by the radiation pressure. A solar sail accelerates with an acceleration of approximately 28.6 km/s when it is nearer to the sun. Solar sails are usually composed of flat, smooth materials that are covered with reflective coatings and supported by the lightweight structures attached to a central hub. The materials used are 40-100 times thinner than the normal writing paper. The laser also produces photon energy therefore solar sail can also be accelerated with the help of laser lights. The solar sail need not carry any type of energy source or carry the fuel like the rockets for the propulsion.

Interstellar travel can be made possible with this type of propulsion. While propelling with laser, a large diameter laser light is made to pass on to the sail membrane which gets reflected and moves forward. Generally, current technology took around 5 months to reach mars however NASA scientists stated that lasers propel the sail to mars within three days. Solar sails are launched within a certain orbit. The sail moves around the planet with constant acceleration, this acceleration is different for different sails. For example, cosmos-1 had a constant acceleration of 0.05 mm/s^2 , IKAROS was with 0.01 mm/s^2 constant acceleration, 0.03 mm/s^2 and 1.1 mm/s^2 of acceleration was produced by the Nano Sail-D and Light Sail A, respectively. 0.05 mm/s^2 by DE Orbital sail. The disc-shaped spin-stabilized sail of 15 m radius produces more acceleration with around 0.12 mm/s^2 . So, it is clearer that the movement and acceleration of the sail depend on the size, shape, and stability of the sail.

1.3. History:

Solar sailing has been developed by many researchers and implemented a lot in 1992. However, there were only around 6 solar sails launched on the space successfully and numerous projects are under development. Solar sails are usually differentiated by shape as well as their stability. Regarding shape, there are usually rigid and non-rigid sails, and these get further classified into the square sail, disc sail, and heliogyro. In terms of stability classified as spin-

stabilizing and three-axis stabilized. Each type of sail has its advantages as well as disadvantages.

1.3.1 Znamya 2:

This is a disc-shaped spin-stabilized sail made of aluminized- mylar sheet, with an area of 314 m^2 . This sail mass is very huge with 6000 kg. Although deployed successfully by Russia, it did not show any propulsion.

1.3.2 Znamya 2.5:

This is similar to Znamya 2 but with a 490 m^2 area. This mission failed due to the burn of sail.

1.3.3 Cosmos 1:

Cosmos1 is the first heliogyro solar sail. The mass is around 100 kg. It is launched in 2015. Each blade of this sail is 15m long with an entire area of 600 m^2 . Unfortunately, this mission also failed due to the rocket failure.

1.3.4 IKAROS:

Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS) was designed by Japan Aerospace Exploration Agency (JAXA). This was the first successful mission launched in May 2010. This is a square-shaped spinning satellite with an area of 200 m^2 and a mass of 315 kg. This satellite used the wire booms to support the sail and to pack easily. Extra masses are placed on the booms for obtaining stability. Each corner consists of Liquid crystal display panels through which electricity is generated to possess attitude control. However, it has drawbacks including the deployment that is more challenging and requires a complex mechanisms as it is a square-shaped sail. The characteristic acceleration is much smaller with about 0.01 mm/s^2 .

1.3.5 Nanosail-D and Nanosail-D2:

This is a square-shaped three-axis passive stabilized sail that is very small in mass and size with 3 kg and 10 m^2 , respectively. This sail was made by rolling up the semi-rigid booms. These are the curved metallic strips that help in packing the cube sat easily. As it is the passive stabilized sail, the attitude control is done by

using permanent magnets to provide stability. Nano sail-D was launched by NASA by the rocket Falcon 1 in august 2008. Nano sail-D was failed in orbit due to the problem in Falcon 1. NASA as a replacement launched another satellite with the sail named Nanosail-D2 in 2010 to complete its mission. This time NASA launched with the rocket Minotaur 4.

1.3.6 Deorbit Sail:

Deorbit Sail is similar to that of the light sail A, the only difference is in the size. This sail is a square--shaped three-axis stabilized sail with an area of 25 m^2 and relatively less mass of 3 kg which helps in launching a cube sat. Attitude control to this sail is given with the help of momentum wheels and magnetorquers. This was launched successfully with the PSLV rocket in July 2015 but this sail did not get into a stable position in the orbit. This was made by the Surrey Space Centre of the European Union. This satellite is mainly based on the components of 3 U Cube sat and commercial-of-the-shelf (COTS). The main objective of this mission is to demonstrate the deorbiting of sail with the aerodynamic drag.

1.3.7 Light Sail projects:

Lightsail 1 and Lightsail 2 are the solar sail satellites from The Planetary Society. These are launched in successive years. Both of these are square-shaped three-axis stabilized sails in a 3U Cube Sat. The area and mass are 32 m^2 and 3 kg, correspondingly. For the attitude controlling, the momentum wheels and magnetorquers were used. Lightsail 1 was launched on 20 May 2015. The purpose of this was to check out satellite's systems however the orbit in which the sail deployed was not high enough to escape from the Earth's atmospheric drag. These projects demonstrated solar sailing properly. Lightsail-2 was launched on 25 June 2019 and deployed on 23 July 2019. Unlike the Light Sail 1, it was launched into a much higher low earth orbit.

1.3.8 Projects in development:

Several projects are currently in development, including Gossamer-1, Inflate sail, NEA Scout, Lunar Flashlight, Surrey Cube Sail, Illinois Cube Sail. Sunjammer has been canceled. Sunjammer is the biggest sail planned to develop in the year 2015 but due to the complexities involved in manufacturing such a big sail, it was

canceled. Despite this, several sails are planning to launch in the future. Gossamer-1 and Surrey Cube sail are the square-shaped three-axis stabilized sails with an area of 25 m^2 each and masses of 25 kg and 3 kg, sequentially. These are planning with different attitude controls with attachment to launch vehicle for gossamer 1 and momentum wheel, magnetorquers, and translational stage for Surrey Cube Sail.

NEA Scout sail and lunar flashlight sails are similar sails that are in development. These are square-shaped three-axis and spin-stabilized sails with an area of 80 m^2 and 12 kg of mass. These are expected to achieve an acceleration of 0.06 mm/s^2 . Inflate sail has been developing since 2017, it is a disc sail with three-axis stabilization with a sail area of 10 m^2 and only 3 kg mass. Momentum wheels and magnetorquers are used for the attitude control here. There are numerous missions under development. For instance, Illinois Cube sail, Gossamer-2, Gossamer-3, Geo Sail, Geostorm, Pole Sitter etc.

1.4. Novelty of Work:

This shows why the spin-stabilized and disc-shaped sail is different and desirable than the other sails. Even though three-axis stabilized sails produce fast attitude maneuvers, these are only applicable to the smaller sails because of the mechanical complexity involved. The better attitude performance, as well as the deployment, is essential for the solar sail. Znamya-2 and Znamya-2.5 were the disc-shaped sails with spin stabilization but these were failed because of the attitude control and huge mass of the sails. Though the sail designing is similar to that, the attitude controls are different. In the previous sails, controls were given by the cargo spacecraft attached to it but now it was made simpler and accurate. The attitude controls are given by the LCD panels with the on/off technique. The cube sat is used so that the mass is relatively less compared to the previous missions. This helps in providing more acceleration that makes the sail move to other orbits in less time. Moreover, there is a large difference in size also. When it comes to the control mechanism, this work is slightly nearer to the IKAROS sail but not the same. The shape is completely different from the IKAROS which was a square-shaped sail.

This work focuses on:

- Designing of a disc-shaped spin-stabilized sail and other sails and their thermo-structural analysis.
- Determining the attitude controls for the sail.
- Determining the attitude and orbital dynamics.
- Building a solar sail deployment demonstrator and discussing the packing technique and deployment method.

CHAPTER 2

LITERATURE SURVEY

ODISEE- A proposal for demonstration of a solar sail in low earth orbit.

M.Leipold, C.E. Garner, R. Freeland, A. Herrmann, M. Noca, G. Pagel, W. Unckenbold (1999)

This study showed that a low-cost solar sail innovation show mission in the Earth circle is possible. ODISEE mission is the suitable mission which is the suggested approach for the improvement of this high-level technology of utilizing sun-oriented radiation pressure for essential attitude control and propulsion. The mission, proposed for dispatch in 2001, shows and approves the fundamental standards of sail manufacture, packing, storage, deployment, and control. These principles are shown in this project for the designed structure. The aluminized sail film is collapsed and bundled in little space holders. Discharge of the sail is done by deployable less-weight carbon fiber blasts and effectively utilized a chilly gas miniature engine framework for coiling. The sail is directed by facing the Sun during every circle. By expanding the orbital energy it reached the end goal of raising the circle of the solar sail space apparatus. On-board cameras are predicted to notice the sail sending, and an extra science payload gives far off detecting information of the Earth.

Solar Sail Orbit Operations at Asteroids: Exploring the Coupled Effect of an Imperfectly Reflecting Sail and a Nonspherical Asteroid.

Esther Morrow, D.J. Scheeres, Dan Lubin (2002)

This paper focuses on the operations of the sails at asteroids and the hovering points where these should be placed. These hovering points rely upon sail attitude dynamics, the mass of the asteroid, and the speed increase of the sail. For a given separation from the asteroid and sail speed, the sail attitude is determined to maintain that position for extended periods. It has additionally been shown that few orbital choices are accessible that offer great inclusion of the asteroid and that neither affects the surface nor escape. These circles are steady and sun coordinated. A sail could keep up the circle for expanded timeframes in such a

circle. A few asteroids (like Eros) require little sail speed increases for orbital tasks to be achievable. In such cases it is important to decrease the sail speed increase, changes in the sail region can be managed. With the exemption of twist balanced outsails, the organization instrument could be switched so the sail could be mostly refolded.

Design study of a square solar sail architecture.

G. Greschik, M.M. Mikulas (2002)

The effect on feasible execution and the structural attributes in 10x10 m square-shaped solar sails of different plan boundaries are investigated in this survey. Upper-bound execution is issued with the engineering of reasonable mechanicals and the extreme primary productivity in this class of sails due to the tension in one direction in every quadrant part, to be specific, the sail with strips. The designs are demonstrated with a cutoff point well-disposed methodology. These developments are supported by evaluating reaction essentials including sail surge, blast mechanicals, and operating disappointment modals. The perceptions and ends advance the best in class in sail plan and give direction to future designing.

Scalable solar sail subsystem design.

David M. Murphy, Thomas W. Murphey (2002)

An improved solar sail, which incorporates gossamer coil able longeron pole technology, has been created. Basic dependable arrangement and the reliability with the least weight are given. This solar sail system is additionally interesting as it is made out of films that are tensioned with not having the fuse of catenaries. This arrangement is made conceivable by not considering the primary wrinkling due to the propulsion. The mathematical demonstration of wrinkling is considered and calculated for the designed sail. The sail bundle is a mass-streamlined subsystem that is mounted to an overall space apparatus to give the persistent low-level push. The planned standard is a three-hub balanced out on a square sail with 40 m quadrants. The attitude controls are given by gimbaling the rocket on an all-encompassing blast. The standard plan definition was considered and the subsequent design sail versus size is examined.

Solar sail technology development and demonstration.

Liepold, Eiden, Garner, Herbeck, Kassing, Niederstadt, Kruger, Pagel, Seboldt, Schoppinger, Sickinger, Unckenbold (2003)

The paper stated the fundamental consequences of testing on grounds and suggested the following stages in solar sail innovation advancement. This innovation started the guarantee by fundamentally upgrading the outer planet exploration for less effort space investigation missions. An inexpensive photon sail technology in earth-centered orbit and its near-space deployment test is demonstrated. By promising outcomes acquired during the study concentrated by the DLR (in participation with NASA/ JPL) and the ESA. Considered the first significant achievement. A breadboard model of 400 m² was created, fabricated, and tried by the end of 1999. It exhibits the attainability of a completely less weight deployable solar sail membrane structure in reenacted ambient climatic conditions.

Solar sail Attitude control and dynamics.

Bong Wie (2004)

Attitude controls and dynamics of the sail are determined. Bong Wie published two papers in controlling and dynamics of sail. Initially, attitude controls were stated in the first part. Further later, solar radiation pressure, Centre of mass and Centre of pressure offset equations, dynamic equations of motion with earth pointing and sun pointing in an earth-centered orbit were derived. These were done for spin-stabilized square sails of 5776 m² and 1600 m² surface area. The second part published in the advancement to part-1. Various dynamic models and control design options for sail are presented. This work is used for deriving the attitude dynamics of the disc spinning sail designed.

Optimal Solar Sail Trajectories for Missions to the Outer Solar System

Bernd Dychtwald (2005)

The optimal solar trajectories for outer solar system missions are discussed. The orbital analysis, and the trajectories are calculated by the force models, orbital dynamics and the trajectory optimization method. The orbital dynamics and trajectories for the spinning sail in sun-centered orbit are derived.

Attitude control design for a sail flight validation mission.

Bong Wie, David Murphy (2007)

This paper determined the design of the attitude control of a solar sail for a sail flight approval mission proposed in a daybreak sunset sun-coordinated orbit. This solar sail attitude control framework design comprises a propellantless essential disposition control system and the micro thruster-based optional control. The essential disposition control utilizes two counterweight masses run along with pole cords for the pitch and the yaw trim control and move stabilizer bars at the pole tips for motion control. The optional disposition control framework utilizes lightweight beat plasma engine modules are mounted at the pole tips. Such a small-sized thruster-based optional disposition control design can be utilized for attitude moves from different conditions. Including effectiveness, which can't be taken care of by the propellantless essential attitude control? The general straightforwardness, adequacy of the proposed solar sail attitude control design is exhibited for a sail flight approval mission utilizing a 40-m, 150-kg sail craft in a 1600-km day-break nightfall sun-coordinated orbit. The proposed solar sail attitude control is relevant with negligible adjustments to a wide scope of future solar cruising missions with changing necessities and less complex missions.

**CubeSail: A low-cost CubeSat based solar sail demonstration mission.
Vaios Lappas, Nasir Adeli, Matthew Perron (2011)**

The application of this work is the designing a CubeSat based sail demonstration mission. Regarding this aspect, this research stated the cube sail mission, deployment with the cube sail, controlling, and the cube sail satellite bus. The cube sat missions are low in cost and also payload will be less. The sail designed in this study is made as a cube sat mission by analyzing the data stated here about the cube sail satellite. Disc spinning sail with a sail area of 175 m^2 is placed in a 12 AU cube sat.

**Solar Sail Science Mission Applications and Advancement.
Malcolm Macdonald, Colin McInnes (2011)**

Solar sailing has been visualized as an empowering or problematic innovation. The guarantee of open-finished missions permits the thought of fundamentally new directions and the conveyance of spacecraft to various outer places. A

mission list is introduced with a broad scope of advantages of the potential sail. This study Permitted recognizable features of the critical highlights of missions which are enhanced through this sail. From these a sail application-pull innovation improvement guide is set up, utilizing every mission as an innovation to the next. The advancement of new technologies, particularly for space applications, is high-hazard. This study suggested that this critical innovation be utilized to show progression in the solar sail shortly soon. These progressions are achieved through coupling and other advances by improving the current sail innovations.

NanoSail-D: A solar sail demonstration mission Les Johnson (2011)

This article stated the failure of NanoSail- D launched in 2018 due to the deployed ejection system. Separate booms and other functional parts of the sail are functionally tested separately and with sub-assembly. The main target of this research is to reduce payload to get certain acceleration with smaller sail without technical risks. Considering, the failure of sail due to the failure of deployment of the membrane and the reduction of payload to get the desired acceleration. In this work, the deployment demonstrator of sail with reduced payload by using a cube sat is designed and then demonstrated.

Status of Solar Sail Technology within NASA. Les Johnson, Roy Young, Edward d Montgomery, Dean Alhorn (2011)

This survey paper sums up NASA's interest in solar sail innovation to date and examines future opportunities. NASA gained generous progress in the improvement of the solar sail. Use of the sail in mechanical science and investigation of the close planetary system determined. Till now NASA developed 2 different sails. NASA has effectively finished useful testing of vacuum. The sail construction, adaption to one-climate and one- gravity climate stated. Their possibility for the sun-centered orbits with further extensions is also determined which were taken into consideration for the project. Calculation demonstrating and scientific reproductions were shown in the survey. The adaptability of the sail to the larger sizes that are needed to actualize the original of missions utilizing solar sails is determined. Besides, life and space ecological impacts testing of sail and segment materials were likewise stated. NASA's subsidizing for these planets was

stated clearly in the survey. The Nanosail-D mission was planned to board on Falcon-1 rocket, dispatched in 2008. Because of the disappointment of that rocket, the Nanosail-D was never effectively allowed the chance to accomplish circle. It was launched in the fall of the year 2010.

On-orbit verification of fuel-free attitude control system for spinning solar sail utilizing solar radiation pressure.

Ryu Funase, Yoji Snhirasawa, Yuga Mimasu, Jun'ichiro Kawaguchi (2011)

An on-orbit fuel-free attitude control system is designed. The attitude control system design is given for a spinning sail satellite that utilizes only solar radiation pressure and solar energy for the sail movement. To design fully the RCD, attitude control logic and control performance, and on-orbit are verified. The sail attitude control system with no fuel and solar radiation pressure exerted on the sail membrane is derived from this research work.

Japanese deep sail demonstration mission.

Yuichi Tsuda, Osamu Mori, Jun'ichiro Kawaguchi (2011)

This paper depicts the achievements of the IKAROS solar sail, the first effective solar sail which traveled to other planets. This paper also depicted the working of the IKAROS space apparatus framework and stated how the IKAROS sail has been worked. Achievements of sail before the finish of this project stage. It was designed by the Japan Aerospace Exploration Agency (JAXA) and it was launched from Tanegashima Space Center on May 21, 2010. IKAROS effectively conveyed a 20 m-range sail on June 9, 2010. From that point forward IKAROS has performed interplanetary solar cruising exploiting an Earth to Venus exploration. By December 2010, the mission is completed. The IKAROS is considered while determining the angular rate and characteristic acceleration of the sail designed in this project.

Impact of optical degradation on solar sail.

Bernd Dachwald, Malcolm Macdonald, Colin McInnes (2012)

A parametric model is utilized for depicting the optical debasement of the film with its ecological history. Assess the effect of various corruption practices on this sail project execution for some models interplanetary missions. The missions related

to reaching the mercury, quick sail transmission to Neptune and the heliopause and counterfeit Lagrange- point missions are demonstrated. This paper mainly focuses on the optical properties of the polyimide films that are coated thin. The expectations on sails are probably going to be influenced by the harmful impacts of the space climate, yet their genuine debasement conduct is generally not known. The standardized sail power models that are right now utilized for solar sail mission examination and configuration is not considering these impacts.

Solar Polar Orbiter.

Malcolm Macdonald, Gareth W. Hughes, Colin McInnes (2012)

An evaluation and introduction of a solar polar orbital sail have been stated in this paper. This study focused on the advancement of deliberately significant advances of similar technology to future scientific innovations. The innovation is solar cruising. The utilization of characterized solar sail is deduced. The essential mission design uses the greatest Soyuz Fregat 2-1b dispatch energy. The sail was sent not long after the Fregat division. The 153 x 153 m square sail at that point twisted into a round 0.48-galactic unit circle. The circle tendency is raised to the right angle concerning the sunlight-based equator giving it a little more than 6 years. Both the sail and space apparatus innovation necessities have been determined. The sail requires progressed blast and new thin-film innovation. The spacecraft climate is generally generous when related to other missions like the Solar Orbiter mission and BepiColombo. Therefore, the spacecraft technologies were discovered to be insignificant.

Demonstration of 20 m solar sail system.

David Murphy, Michael McEachin, Brian Macy, and James Gaspar (2012)

In this report, a demonstration of a 20-m solar sail system has been stated. The recent design developments to the functionality of the S4 sail craft are stated. The materials are tested and the fabrication experiences are determined. The investigation is presented to a point where projections for framework execution have started to have genuine validity. The materials used for testing are thermal reflectance materials as these are the only materials that were used in solar sailing to reflect a large number of photons. Sail innovation is showed that assess the mechanical availability of solar cruising and the flight assessment. The testier

and predictive analysis of this sail design is demonstrated. A sail similar to this is used as a reference sail in this project. The similar sails like a LightSail and NanoSail. The payload of the sail is reduced to get certain characteristic acceleration to the much smaller sail without any technical risks.

Exploring Geomagnetic tail using small solar sail.

Colin McInnes, Malcolm McDonald (2012)

The geomagnetic tail projects require a space apparatus to be infused into a long-curved circle to investigate the spatial design of the geomagnetic tail. Nonetheless, the fact that the circular sail is fixed inertially, and the geomagnetic tail is coordinated through the line between sun and earth. The apse line of the curved circle is accurately lined up with the geomagnetic tail just once consistently. These require response mass that will eventually restrict the mission lifetime. It is shown that sun-coordinated line precession can be accomplished utilizing just a little, minimal effort solar sail. Since solar sails don't need response mass, a geomagnetic tail mission can be designed that gives a consistent return by forever positioning a payload inside the geomagnetic tail.

Solar sail Halo orbits 2: geocentric case.

McInnes, C. R., Simmons J. F. L. (2012)

The investigation of the dynamic stability of the various orbits and showed linearly stable families of halo orbits exists. The square-shaped solar sail is investigated. The square-shaped sail is placed in a cube sat and it was similar to that of the LightSail-1, NanoSail, and LightSail-2. The dynamic equations and solutions of that are given the three different modes such as the polar synchronous mode, general synchronous mode, and the halo mode are considered. The stability of halo orbit and their patched halo orbit trajectories are stated. The solar sails on the halo orbits are used on a planetary night to study the geomagnetic tail. The real-time stereographic investigation is made in this study.

Artificial Lagrange Points for Partially Reflecting Flat Sails.

Colin R. McInnes (2012)

This paper presented the artificial Lagrange points for partially reflecting flat sails. The sail reflectivity affects the space required for the artificial Lagrange point. The

equilibrium solutions for the ideal flat solar sail and the partially reflecting solar sail are given. The correction was given with the horizon sensor for the earth. These sails are used to produce artificial Lagrange points. This stated that partially reflecting sails produce Lagrange points and the non-reflecting sails will be placed in a smaller volume as possible. The main reflective sensitivity of sail is due to the main Centre line angle as it usually affects the solar radiation pressure vector by limiting it.

LightSail-1 Solar Sail Design and Qualification.

Chris Biddy and Tomas Svitek (2012)

This paper examined the plan difficulties, special design features, and system verification for LightSail-1. LightSail-1, a task of The Planetary Society, is a Solar Sail Demonstration mission based on the Cube Sat stage. Heavenly Exploration Inc. planned, constructed, and completely qualified the Solar Sail module for LightSail-1. This incorporates a blast deployer instrument that stows an all-out blast length of 16 meters (4 x 4-meter blasts) which are utilized to convey a 32-m² sail film in a 2U bundle. This plan uses the unbending TRAC blast created by AFRL (Air Force Research Laboratory) for conveying and tensioning the layer that makes up the sail. To boost the size of the solar sail, the blast deployer took on a unique shape to boost bundling effectiveness. This accomplished 80:1 conveyed to present proportion.

Achievement of IKAROS — Japanese deep space solar sail demonstration mission

Tsuda, Mori, Funase, Sawada, Yamamoto, Saiki, Endo, Kawaguchi (2013)

IKAROS flight demonstrator placed in sun-centered orbit to reach Venus is designed. The sail's successful deployment, orbital acceleration, navigation technology, trajectory analysis are stated in this paper. The sail deployment and orbital analysis is given to the sail using the above-mentioned paper.

Generalized Attitude Model for Spinning Solar Sail Spacecraft.

Yuichi Tsuda, Takana Saiki, Ryu Funase, and Yuya Mimasu (2013)

Generalized attitude control for spinning solar sail spacecraft is given here. To derive GSSM the essential parameters for attitude motion of spin sails are verified using IKAROS. Also, Generalized and physical interpretation of spinning solar sail

is derived and evaluated using the IKAROS sail. This is very similar work to this project as spinning sail is taken into consideration here. Therefore, these verified and evaluated parameters and motion controls are considered for designing the disc spinning sail.

Heliogyro Solarsail.

W. Keats Wilkie, Jerry E. Warren, Jer-Nan Juang, Robert Bryant (2014)

This paper presented an outline of continuous heliogyro innovation improvement and achievability appraisal activity inside NASA. The IKAROS sail which was gone successful was created an interest and scope in the other solar sail designs with high utilities. The IKAROS is a spin-stabilized sail in the shape of a square whereas heliogyro is also the spinning sail but it has blades-like structure. The heliogyro solar sail, specifically, is being reconsidered as a likely important design for future solar cruising missions. Specifically, a limited-sized heliogyro solar sail innovation idea was portrayed. Likewise, the progression and the underlying elements and controls of the heliogyro design were examined. Demonstrated a structure of future heliogyro advancement work coordinated towards empowering a minimal effort heliogyro innovation exhibition mission ca. 2020. The heliogyro is considered as one of the reference designs in this project.

Coupled control of reflectivity modulated sail for geosail.

Junshan Mu, Shengping Gong, Jun Feng Li (2014)

The utilization of the electrochromic gadget is introduced for the shuttle's attitude controlling since its optical qualities can be modified by generating the magnetic field. The innovation was utilized and checked effectively on IKAROS, this sailing craft is used as one of the reference sails in this project. The reflectivity control gadget can likewise be utilized for the circle control of the sail. In this investigation, another methodology for joint dynamic circle and disposition control of a sail utilizing the reflectivity balance innovation is proposed. The power and force models of a reflectivity balanced turning plate sail experienced by solar radiation pressure are examined. The two reflectivity tweak modes and control execution are given. The exhibitions for the geo sail are demonstrated numerically and the utilization of ordinary regulator is determined.

Sunjammer: a preliminary end-to-end mission design.**Jeannette Heiligers, Ben Diedrich, Billy Derbes, Colin R. McInnes (2014)**

This paper demonstrates the NASA mission of a large sail which is named Sunjammer, it was a spin-stabilized sail planned to start in the year 2014. Unfortunately, this mission got stopped and not implemented further. However, the technology and the other structural and mechanical dynamics stated can be used shortly soon. This sail focuses on the sub-L1 orbit for cutting-edge sun-based tempest cautioning. Compared to the sails designed till now the Sunjammer solar sail is recorded to have the highest characteristic acceleration which helps in moving to the other planets quickly. This focuses (AEPs) in the sub-L1 orbital area available by the Sunjammer sail just as solar sail Halo circles are explored. Therefore, the fly-out from an Earth GTO into either a chosen sub-L1 AEP or Halo circle is streamlined for a compromise between the ΔV to be given at GTO perigee and the hour of flight. Moreover, fascinating, time-ideal stretched-out mission situations are introduced to support future solar sail mission applications. For example, the sail moving to an AEP high over the ecliptic plane for high-scope Earth perception. All investigations are done both for an ideal Sunjammer sail execution just as for a reasonable exhibition got from a sail primary examination. An examination of the outcomes showed that non-ideal sail properties increment the hour of flight of the directions by 2.4 - 7.9%.

Solar sail technology- A state of the art review.**Bo Fu, Evan Sperber, Fidelis Eke (2016)**

In this research, the present solar sail technology is reviewed. This stated various solar sail designs, dynamics, attitude controls, design and deployment mechanisms present, and the various trajectory analyses. This paper has taken into consideration and the various sails of different shapes and stabilizations were designed and compared to each other. The desired design is selected from that and the suitable control from the various controls mentioned in this paper is also given to the sail. Not only technological difficulties but also current challenges in solar sailing are identified. The possible sail which meets the current needs with the low difficulties is designed.

Correction and adjusting for the deformation on solar sail.**Fan Shen, Siyuan Rong, Hualan Zhang, Fuun Peng, Naigang Cui (2016)**

Solar sail deformation and the correction and adjusting of the deformed sail are analyzed. The solar pressure principle and finite element analysis is used for the correction. The multi-point models are set and simulated using ABAQUS for obtaining the structure parameter change. The lift mechanism has been stated and the sail deformation is controlled. The sail deformation is analyzed from the simulation. The deformation factors are observed and calculated for the designed sail using the techniques from this research.

Thermal-structural analysis of a square solar sail.**Luisa Boni, Alessandro A. Quarta, Giovanni Mengali (2018)**

This work is to improve the structural and thermal response of a square solar sail when the solar radiation pressure acted on it. Here a sail of 20 m is considered at a distance of 1AU from the sun. The analysis is carried in such a manner that the temperature field is responsible for stress- displacement solution without inverse dependency. The software used here for the analysis is ABAQUS/STANDARD. Surface heat flux, solar radiation, the temperature are used as thermal inputs. The analysis is performed on a large sail membrane and booms are made of Kapton sheet and Kevlar, correspondingly. The designed sails in this project are made to undergo thermal-structural analysis in the manner mentioned in this work and the outputs obtained for each sail are compared to obtain the desired model.

Analysis of the solar sail deformation based on the point cloud method.**Xiyao Huang, Xiangyuan Zeng, Christian Circi, Giovanni Vulpetti, Dong Qiao (2020)**

This paper described the deformation of solar sail using a technique based on point cloud and triangular mesh generation. The deformation types billowing and wrinkling are discussed. Solar radiation pressure force and moment are calculated and compared. The simplification, modeling accuracy, and computational efficiency are also investigated. The work is considered to derive the billowing and wrinkling effects on the spinning disc sail. SRP force and moments are calculated using the procedure from this paper.



Fig 3.1: Methodology Chart

3.2 Design:

Solar sails are usually of different designs such as rigid and non-rigid. Rigid sails include square-shaped sails while non-rigid include circular-shaped sails and helio gyro. Irrespective of the shape and size, the sails are made of a reflective surface which is usually a thin film of an aluminized-mylar sheet, aluminized mylar, CP-1, aluminized mylar with chromium, aluminized Kapton, aluminized CP1, and so on. All these are strong, thin membrane structures that reflect the photons from the solar energy by pushing the sail forward helping in the movement of the sail in the orbit. If it gets developed in the future, it is possible to move the sail with huge laser lights that will make the sail reach mars in 21 days unlike, the present technology which takes approximately 130 to 300 days.

Each shape of the sail has its advantages as well as disadvantages. Rigid solar sails require support for their deployment, while non-rigid sails do not require any supporting structures. Rigid structures were used by Square sails, clipper sails, quad, and butterflies. These require supporting structures such as spars and reducing the weight penalties. Usually, clipper sails require four spars and also include complex rigging to prevent the deformation of boom due to the tension in the sail membrane while quad sail requires two spars to increase the mass fraction of the elements. Butterfly sail possesses stability by reducing the weight penalties.

Regarding non-rigid sails, there are two types namely, disc sails and heliogyro. Heliogyro sails have membranes with large length to width ratios, look similar to the helicopter rotor blades. This is not a continuous type structure and it is divided into thin strips-like structures that are symmetrically arranged around the hub of the sail. These blades have a c_m in the hub and provide centrifugal force throughout the structure. These were unreeled after getting deployed whereas in the other sails the more membrane is unfolded after deployment. The larger the blades of the sail, the membrane bending, twisting, and flexing play a crucial role in spacecraft performance.

The disk-shaped sail consists of a hub in the center of the sail and the membrane surrounding it. These types of sails do not require steady structural elements for the support due to which wire booms will be installed that are very useful in less

complicated packing. This sail has no complexity involved in the packaging as the deployment. As the sail is circular, it is placed in a small cubical structure with electrical motors for easy deployment. The circular shape does not contain any edge surfaces due to which the area exposed to the solar energy is more compared to the other surfaces.

The stabilization is classified as spin-stabilized and three-axis stabilized sails. Three-axis stabilized sails are the sails that support the sail in three dimensions in which two dimensions are present in the surface of the sail and the third-dimension is perpendicular to the sail. This can be made by attaching booms, masts and, stays to the outer edge of the sail, and also these booms are prevented from collapsing in the third direction. The spin-stabilized solar sail also has disadvantages such as it is difficult to control the sail due to the continuous spinning. Despite the apparent drawback, there are numerous benefits such as it uses centripetal force to keep the sail steady. It did not need extra structural elements for support which makes the sail lighter and due to the spinning of the sail, the sail moves even faster. These types of sails were controlled by moving the sections in and out from the center or by making the satellite tilt to both sides instead of one side.

Due to this, the circular-shaped sail with the spin stabilization is designed and the material used is an aluminized mylar sheet. The membranes of the circular sail are more flexible than the rigid sails. Deployment difficulty is facing in the present sails which will be made less complex with circular spin-stabilized sail as it does not contain any rigid structures for making it steady in the space after deploying. The acceleration produced by the disc spinning sail is more comparatively.

3.2.1 Square Shaped Three-Axis Stabilized Sail:

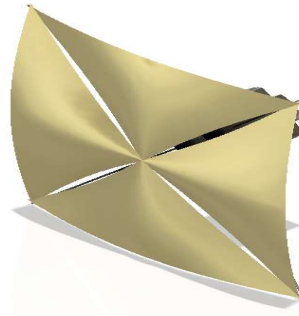


Fig 3.2: Square Shaped Three-Axis Stabilized Sail

This sail is in the shape of a square and looks like a kite as shown in Fig 3.1. 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 is 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 two dimensions of three dimensions lie within the sail surface and the third dimension is perpendicular to the sail. The attitude is controlled by changing its Centre of mass location relative to its Centre of pressure location. This is 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.

3.2.2 Square Shaped Spin Stabilized Sail:

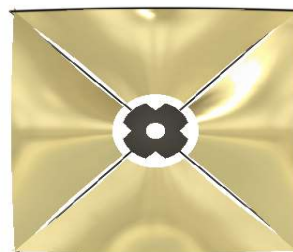


Fig 3.3: Square Shaped Spin Stabilized Sail

The sail is in the shape of a kite but unlike the three-axis stabilized sail as shown in Fig 3.2., 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. The main disadvantage of IKAROS is its acceleration which was not enough for future proceedings. But another sail of this type has been proposed called a Sunjammer. Even though enormous acceleration will be produced by the Sunjammer that mission was canceled due to the huge complex surface area.

3.2.3 Disc Shaped Three-Axis Stabilized Sail:

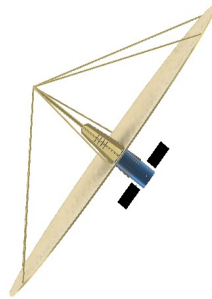


Fig 3.4: Disc Shaped Three-Axis Stabilized Sail

Fig 3.3 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 involved is, it requires stiff booms to make it immune to the Centre of mass and the Centre of pressure offsets. In disc shape more area exposed to sun, unlike the square. Inflate sail is an example of this type and this sail used the Momentum wheel and magnetorquers for attitude control.

3.2.4 Disc Shaped Spin Stabilized Sail:

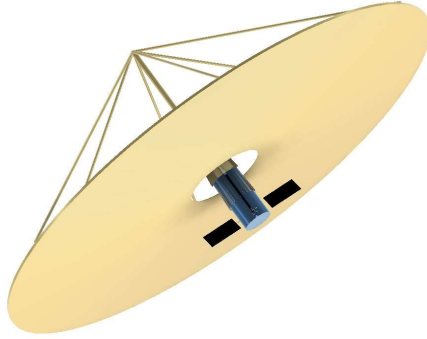


Fig 3.5: Disc Shaped Spin Stabilized Sail

These are circles in shape as shown in Fig 3.4. Spinning disc sails are connected to a structure composed of interlocking masts and booms which surround and connect to the craft. 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 illuminate cities in the Arctic Circle. These sails can be used for future missions. The first sail launched on space Znamya was of this type but it got failed due to technical issues.

3.2.5 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.

3.2.6 Heliogyro:

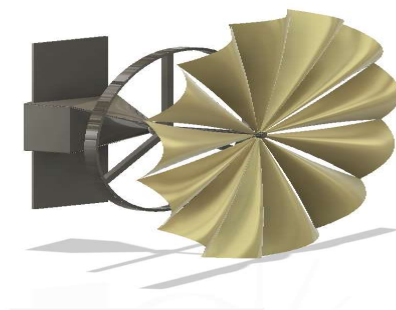


Fig 3.6: Heliogyro Sail

Heliogyro sails are solar sails that are composed of several vanes or blades as shown in Fig 3.5. While deploying the vanes get rolled out and extend directly from the hub due to the spinning motion of the craft. Usually, 8 or 12 vanes can be used. 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 1970's 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 such as flexible membrane, twisting, and bending that play an important role in the performance.

3.3 Solar Sail Configuration:

3.3.1 Disc Spinning Sail:

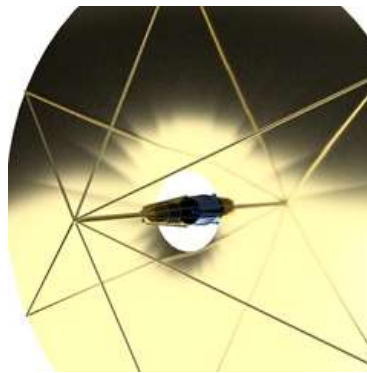


Fig 3.7: Disc Spinning Sail

As discussed earlier, sails are of different types and here disc spinning sail has been taken into consideration which was shown in Fig 3.6. This sail was able to change its attitude to place itself in the sun-centered orbit for the interplanetary mission. Disc spinning sail and the satellite that fulfills the requirement has been introduced. A standard disc spinning solar sail satellite has considered which produces larger angular momentum that prevents external disturbance forces. The size of the sail discussed is 175 m². The sail deployment is made fewer complexes for this sail.

3.3.2 Sail Satellite Structure:

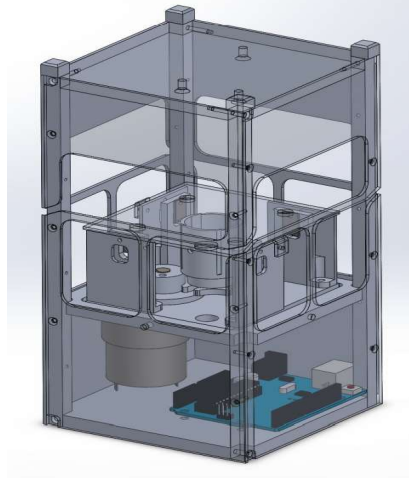


Fig 3.8: 6U Cube Sat

Usually, cube sat is used for this kind of sails because these are more compact and lighter in mass. The cube is made of aluminum with solar cells placed on the outer walls of the cube. The solar cells help in charging the camera, sensors, controllers, actuators, and other onboard control mechanisms. The antennas are placed in such a manner that they are deployed perpendicular to the faces at the corner. The satellite used here is a 6U cube sat as shown in Fig 3.7. That is capable of holding a sail of 175 m^2 . Similar to the satellite in the lunar flashlight sail, here 2 U is used for holding the sail and the deployment mechanism. Other 2 U is occupied by the camera lens, splitting beam mechanism, actuators, and other detectors. 1.5 U is taken by the attitude control systems, data handling, command handling, and power systems. The remaining 0.5 U in the 6 U is the telecom system.

3.3.3 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 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

$$F_c = mr \omega^2 \quad [\omega = (2\pi \text{RPM})/60]$$

$$F_c = 0.5 \times 7 \times 0.105 \times 0.105$$

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

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 which was the successful sail placed in orbit. The sail should possess an angular rate of

$$\omega_n = (F_c / (m \times r))^{0.5}$$

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

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

The sail design is made of aluminized mylar material. This material is of thickness 0.0045 mm and the density is 1.39 g/cm³. 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 m². The sail loading of the designed sail is

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

$$\sigma = 12000 / 1750000$$

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

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

Assuming an efficiency of 90% of radiation pressure at a distance of 1 AU from the sun, the solar radiation pressure is 8.17 $\mu\text{N/m}^2$ 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 m² surface area, the lightness number is approximately

$$\lambda = a_c / 5.93$$

$$\lambda = 0.021$$

Compared to the other sails such as NEA Scout and IKAROS which produce an acceleration of 0.06 mm/s² and 0.01 mm/s², the proposed sail producing more characteristic acceleration.

3.4 Attitude Controls:

Attitude controls of the sail are determined as the steering of the sail after it gets deployed in the orbit. 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 from that 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 and are different for the rigid shaped sails and non-rigid shaped sails.

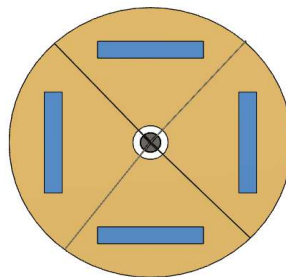


Fig 3.9 Attitude Controlling of Sail

Rigid-shaped sails possess attitude control in several ways. The most effective way is tilting the wings for possessing the control movements of sail and billowing of sail, it is common for the solar sail due to the SRP. This technique is so implemented in any type of sail. Furthermore, momentum wheel, chemical thrusters, and reaction wheels were installed for the attitude controlling in NEA Scout and Lunar Flashlight. Nonrigid sails have been installed with different methods to possess the required attitude control. 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. Nonrigid sails also possess control with the help of passive attitude stability. IKAROS is a non-rigid sail where attitude control is given by the Chemical thrusters and LCD panels.

The attitude controlling for the disc spinning sail designed here is obtained by the reflective devices as shown in Fig 3.8. The reflective devices are of different types including a 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. Even though chemical thrusters and other mechanisms can be used, these techniques are not installed here as the whole purpose of using the solar sail will be affected. The reflective LCD panels are placed on all four sides of the sail with the automatic on/off technique. This helps in the transmissivity of the constant torques and providing the required attitude control to the sail. These devices produce the required transmissivity changes by changing the voltage applied.

CHAPTER 4

THERMO STRUCTURAL ANALYSIS

Thermo structural analysis is one of the applications of the finite element method 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.

4.1 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 payload mass of the solar sail was uniformly modeled and distributed over the entire surface. 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, maximum principal elastic strain, and maximum principal stress are determined.

The analysis of sails is shown below

4.1.1 Heat Flux Analysis

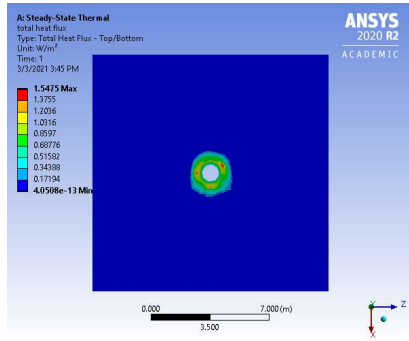


Fig 4.1: Heat Flux of Square Spinning Sail

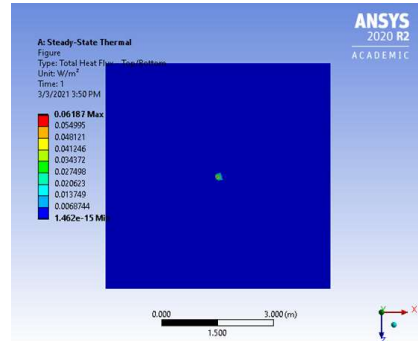


Fig 4.2: Heat Flux of Square 3 Axis Stabilized Sail

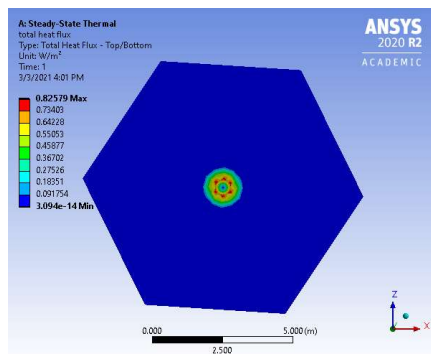


Fig 4.3: Heat Flux of Polygonal 3 Axis Stabilized Sail

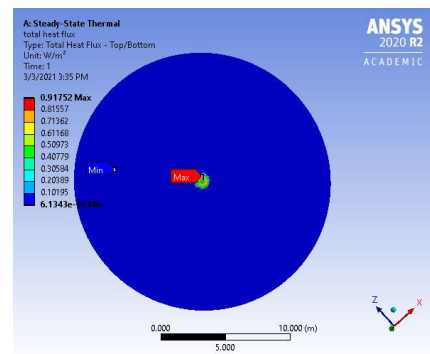


Fig 4.4: Heat Flux of Disc Shaped Axis Stabilized Sail

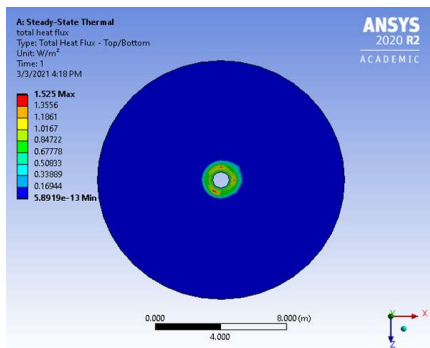


Fig 4.5: Heat Flux of Disc Spinning Sail

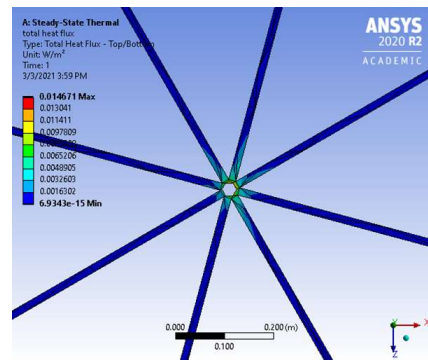


Fig 4.6: Heat Flux of Heliogyro Sail

4.1.2 Deformation Analysis

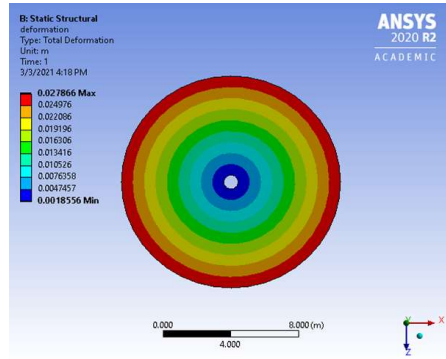


Fig 4.7: Deformation of Disc Spinning Sail

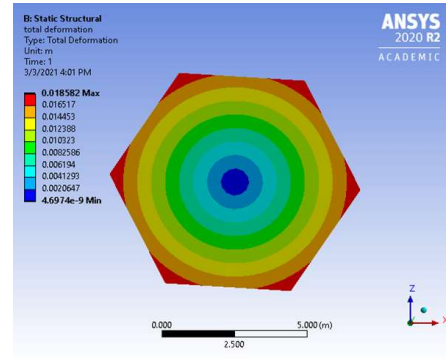


Fig 4.8: Deformation of Polygonal 3 Axis Stabilized Sail

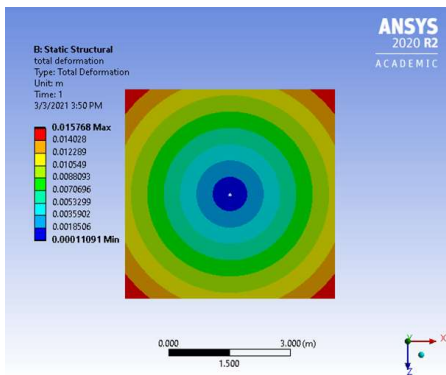


Fig 4.9: Deformation of Square 3 Axis Stabilized Sail

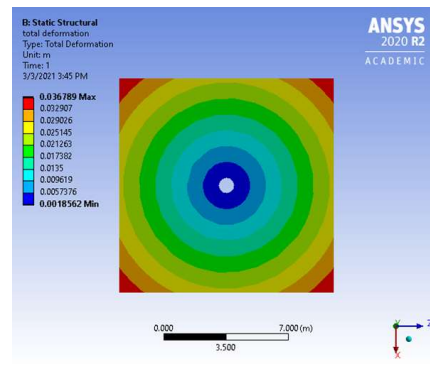


Fig 4.10: Deformation of Square Spinning Sail

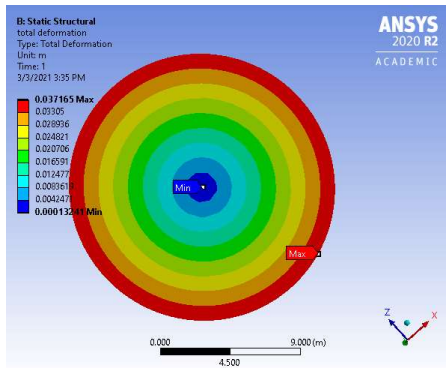


Fig 4.11: Deformation of Disc 3 Axis Stabilized Sail

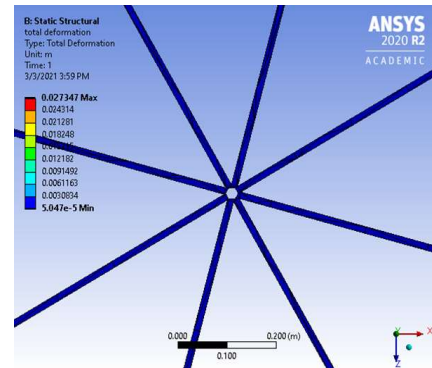


Fig 4.12: Deformation of Heliogyro Sail

4.1.3 Maximum Principal Elastic Strain Analysis

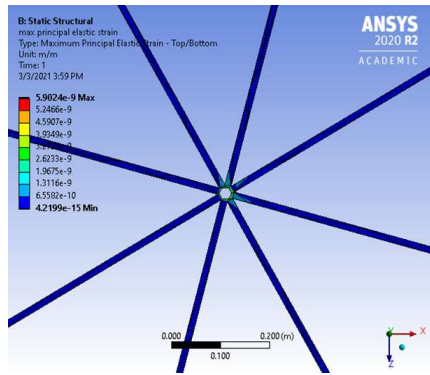
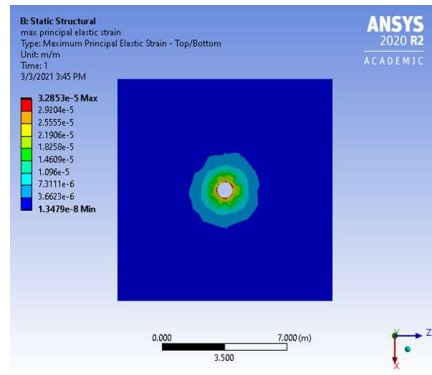


Fig 4.13: Max Principal Elastic Strain of Heliogyro



Fi: 4.14: Max Principal Elastic Strain of Square Spinning Sail

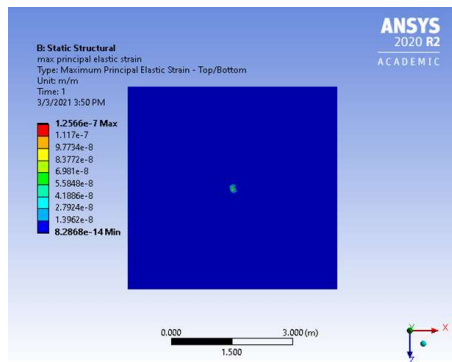


Fig 4.15: Max Principal Elastic Strain of Square 3 Axis Stabilized Sail

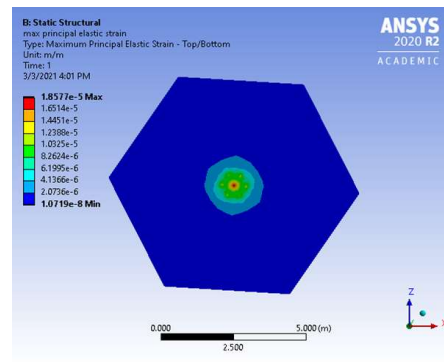


Fig 4.16: Max Principal Elastic Strain of Polygonal 3 Axis Stabilized Sail

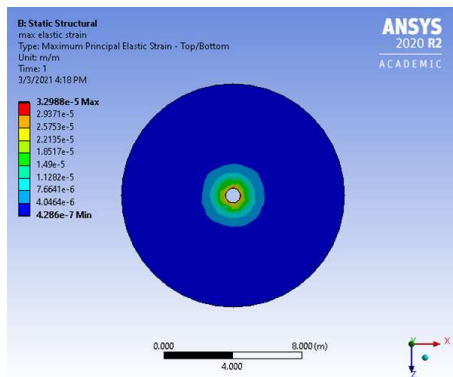


Fig 4.17: Max Principal Elastic Strain of Disc Spinning Sail

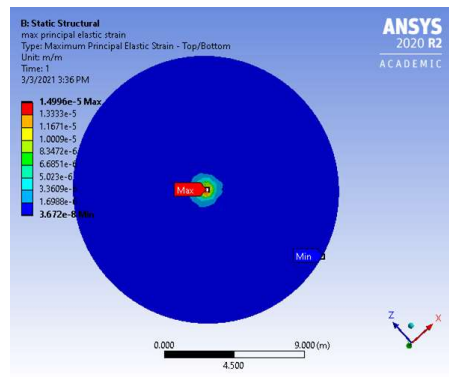


Fig 4.18: Max Principal Elastic Strain of Disc 3 Axis Stabilized Sail

4.1.4 Maximum Principal Stress Analysis

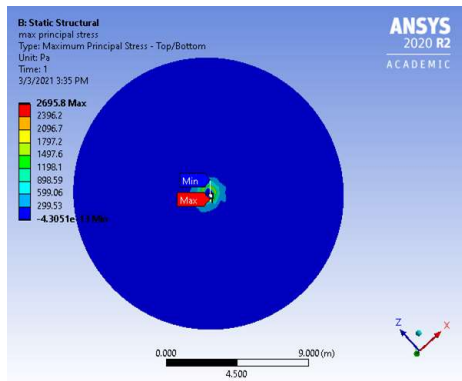


Fig 4.19: Max Principal Stress of Disc 3 Axis Stabilized Sail

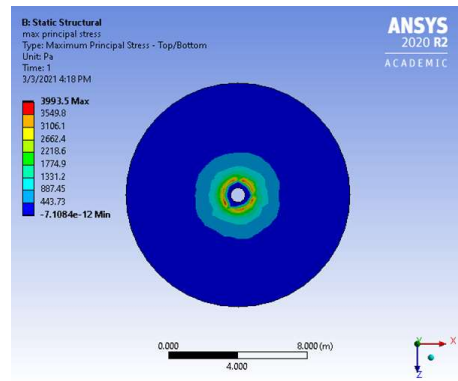


Fig 4.20: Max Principal Stress of Disc Spinning Sail

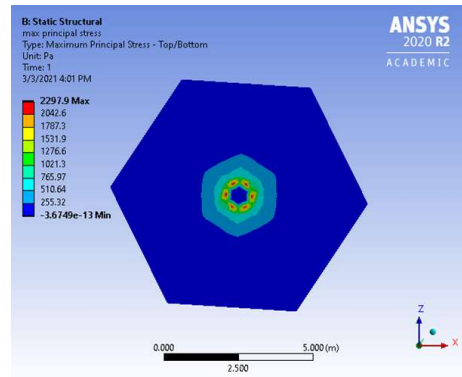


Fig 4.21: Max Principal Stress of Polygonal 3 Axis Stabilized Sail

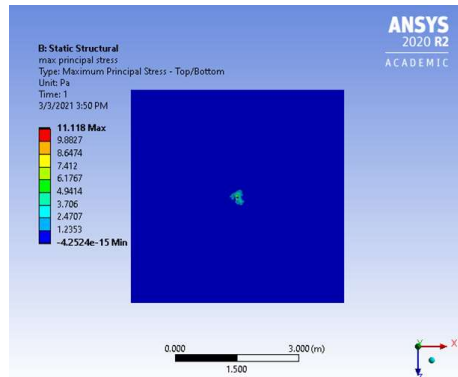


Fig 4.22: Max Principal Stress of Square 3 Axis Stabilized Sail

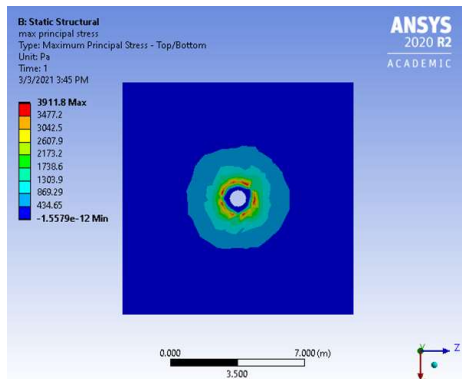


Fig 4.23: Max Principal Stress of Square Spinning Sail

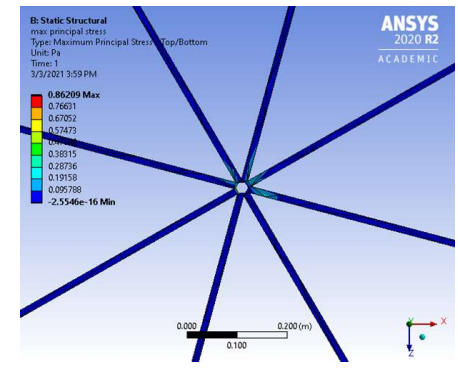


Fig 4.24: Max Principal Stress of Heliogyro Sail

4.2 Comparison:

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

Table 4.1: Analysis Data Comparison

Types of solar sail	Surface area(m²)	Maximum total heat flux(W/m²)	Total deformation(m)	Maximum principal elastic strain	Maximum principal stress
Disc-shaped spin-stabilized sail	175.93	1.525	0.04204	5.25E-06	590.81
Square shaped spin-stabilized sail	195.21	1.5475	0.014312	5.78E-06	638.48
Disc-shaped 3-axis stabilized sail	314.16	0.91752	0.0285	3.30E-07	47.197
Square shaped 3-axis stabilized sail	36	0.06187	0.0090941	8.49E-10	0.064467
Hexagonal shaped 3-axis stabilized sail	64.952	0.82579	0.011657	7.54E-07	128.83
8 blades heliogyro sail	0.88118	0.014671	0.0213701	7.08E-11	0.0070576

4.2.1 Comparison of Heat flux (W/m²)

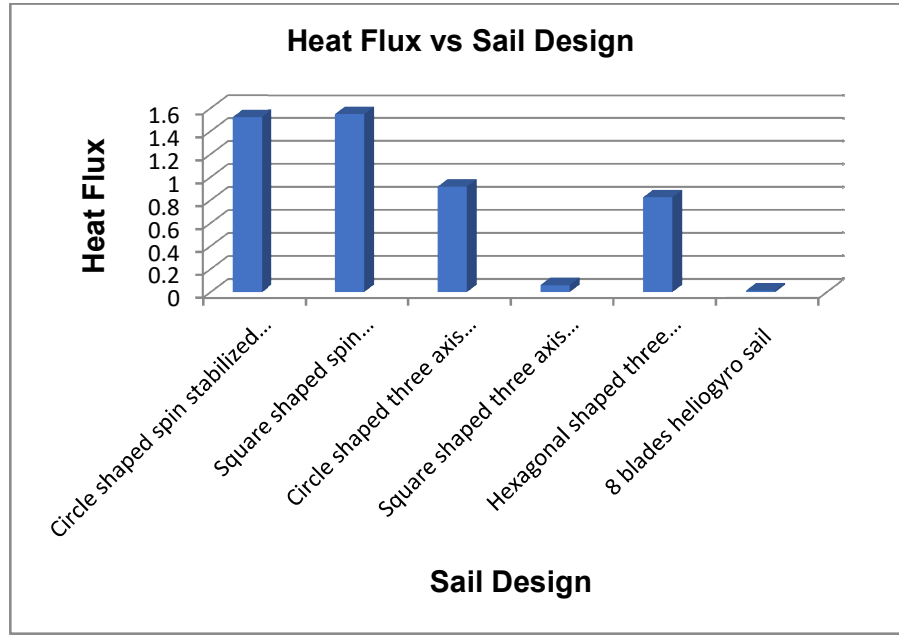


Fig 4.25: Comparison of heat flux

From Fig 4.25, it was clearly stated that the spin-stabilized sails possess a very 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 large 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.

4.2.2 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 sail may possess large deformation due to the light membrane surface and the booms used. The deformation should be smaller as the torque devastating would be smaller and also the controlling ability is easier. Therefore, deformation is made smaller and while designing the sail the

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, the sail with the small deformation is preferred.

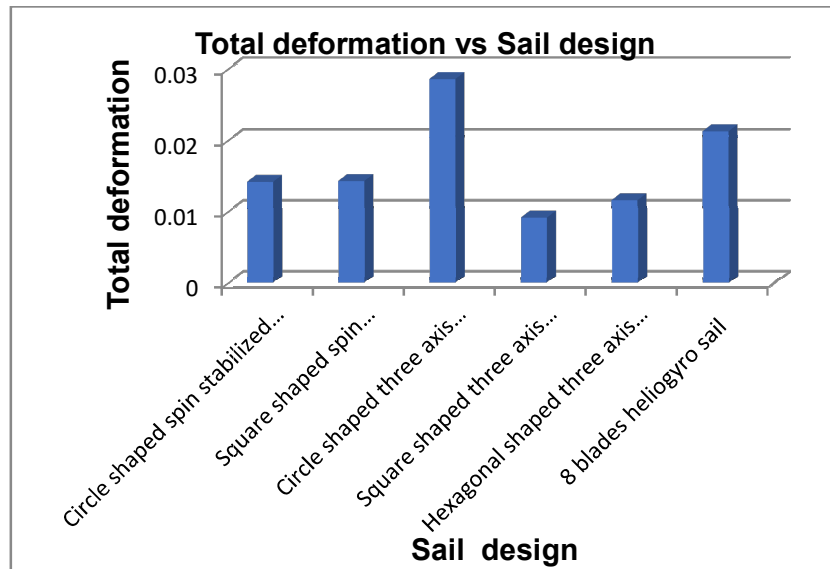


Fig 4.26: Comparison of Total Deformation

Fig 4.26 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 sail of disc, square, and polygonal-shaped has 0.000095, 0.000275, and 0.000172 correspondingly. Heliogyro has the largest deformation ratio of 0.02272. Considering all these values spinning sail is most preferred.

4.2.3 Comparison of Maximum Principal Stress

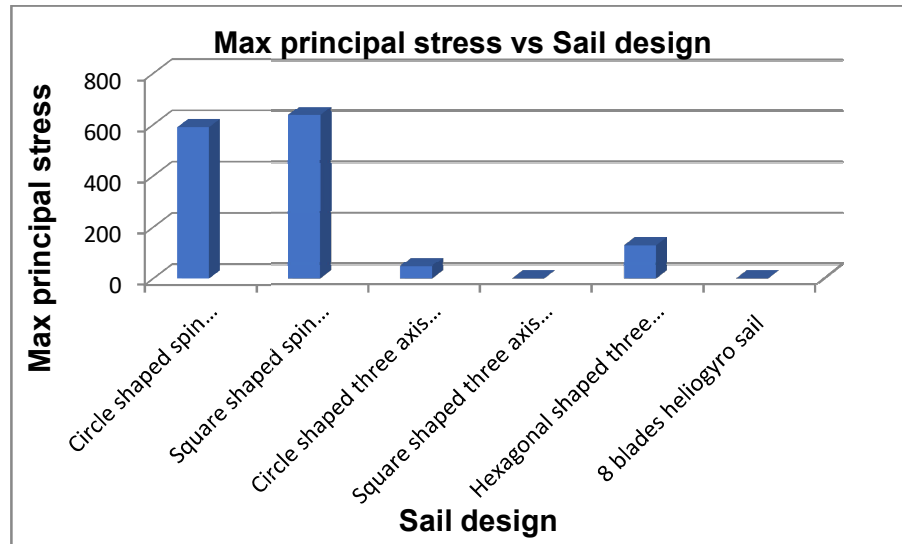


Fig: 4.27: Comparison Of Maximum Principal Stress

Maximum principal stress formula is given as

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

Where, σ_x = shear stress (stress = force/area)
 σ_y = tensile stress

τ = Torque

Hence the maximum stress is proportional to maximum force that can be exerted on the sail surface. As shown in Fig 4.27, the spin-stabilized sails possess more stress compared to other types. Hence these are preferred.

4.2.4 Comparison of Maximum Principal Elastic Strain

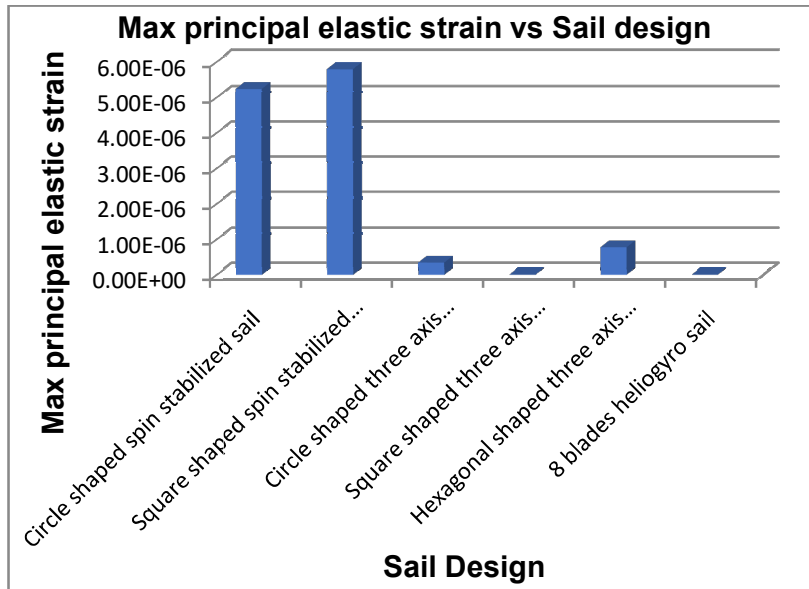


Fig: 4.28: Comparison of Maximum Principal Elastic Strain

By the maximum principal elastic strain theory, the failure occurs when the maximum elastic strain of the complex state of the stress system becomes equals to the strain at the yield point for the complex state of the stress system. The strain at yield point at 0 degrees for the material aluminized mylar is 5% i.e., 0.05.T. From Fig 4.28, it showed that the structures designed did not cross the strain at the yield point. Considering all these parameters and comparisons, the spin-stabilized sail is designed and the circle is designed instead of a square as the packing and deployment technique is less complex. Therefore, a disc spinning sail is designed and deployed.

4.3 Sail Deformation:

Sail deformation is constantly occurring on the sail due to the continuous solar pressure exerted on the sail and therefore wrinkling and billowing of the sail takes place. These effects on the sail surface should be minimized to get the desired acceleration to the sail. Disc-shaped sail with a spinning mechanism reduces the sail billowing by applying a ring to the sail which gives radial tension to the membrane.

4.3.1 Solar Radiation Pressure Force:

Let us assume an ideal flat disc spinning sail as shown in Fig 4.29. The solar

radiation pressure is perfectly reflected from the surface of the sail. Therefore, the force generated on the sail for the incident and reflected photons is the same.

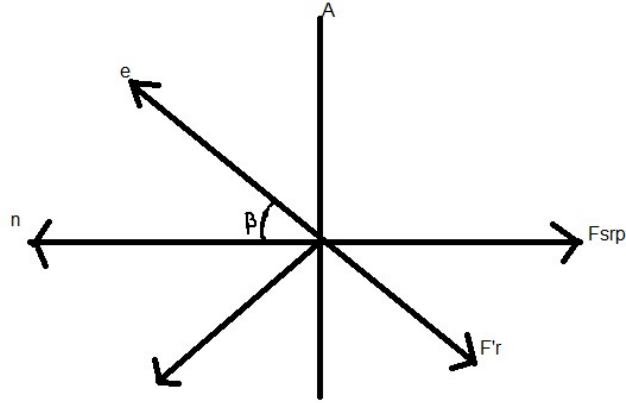


Fig: 4.29: Solar Radiation Pressure

The pressure from incident solar photon impact is:

$$F_r = PA (e_r \cdot n) n_i$$

Where, P is the solar radiation pressure at 1AU from sun = $4.563 \times 10^{-6} \text{ W/m}^2$
 n_i is the unit normal vector that is derived based on the three corresponding nodes

$$A (e_r \cdot n) = \text{projected area}$$

The solar pressure generated for the reflected photons is:

$$F'_r = - PA (e_r \cdot n) n_i$$

The total solar radiation pressure is given as

$$F_{srp} = F_r + F'_r$$

$$F_{srp} = 2PA (e_r \cdot n) n_i$$

Assuming the angle between light array and the normal direction of the membrane as β

$$F_{srp} = 2PA (\cos^2 \beta) n_i$$

The total force on the surface is given as

$$F_{\text{total}} = \sum F_{\text{srp}}$$

$$F_{\text{total}} = 2 \sum PA (\cos 2\beta) n_i$$

The moment on the surface is denoted by M_i and it is the product of distance and the solar radiation pressure force

$$M = \sum M_i = \sum r_i \times F_{\text{srp}}$$

$$M = 2PA (\cos^2 \beta) \sum r_i n_i$$

4.3.2 Billowing and Wrinkling Of Sail:

Billowing and wrinkling of sail take place due to solar radiation pressure force and moment. For billowing, let us consider a surface on the sail as billowed in the two directions, and x , y , and z be the coordinates of the billowed sail. The function of the billowed surface is defined as

$$x^2 + y^2 + z^2 = R^2$$

$$z = \sqrt{(-x^2 - y^2 + R^2)}$$

The function of the billowed sail is given by the $P(x, y)$ and R^2 is the billowed coefficient defined by μ

$$P(x, y) = z = \sqrt{(-x^2 - y^2 + \mu)}$$

$$\text{Here, } x \in (-c/2, c/2); y \in (-c/2, c/2); z \geq 0$$

The deformation degree of the billowed sail changes due to the billowing coefficient and the constant c . The billowing coefficient and the deformation degree are inversely proportional to each other. So that if μ is infinity the sail is flat. Similarly, for wrinkling consider a surface on the sail is wrinkled in the two directions. The wrinkling coefficient is given by λ and the function of the wrinkled surface is $W(x, y)$. The wrinkled surface is given as

$$z = W(x, y) / \lambda$$

Here, $\lambda \geq 1$

The combined deformed function $Q(x, y)$ is obtained by adding the values of z in both wrinkled and billowed cases by keeping the x and y constant.

$$Q(x, y) = P(x, y) + W(x, y)/\lambda$$

μ and λ are dimensionless numbers. The values of these are approximately $\mu=10000, 5000, 2500$, and 1250 and $\lambda = 100, 50, 25$, and 12.5 . The moment of the sail membrane calculated is related to the position of the mass Centre. The change in the c_m occurs along the z -axis which leads to the change of billowing function and the billowing coefficient. The billowing coefficient has to be increased so that the deviation decreases in the z -direction resulting in reducing the billowing. The wrinkling takes place in the x and y direction and the force acting on the surface in these directions is irregular which leads to the changing of the direction and magnitude of the total force.

CHAPTER 5

ATTITUDE AND ORBITAL DYNAMICS

5.1 Attitude Dynamics:

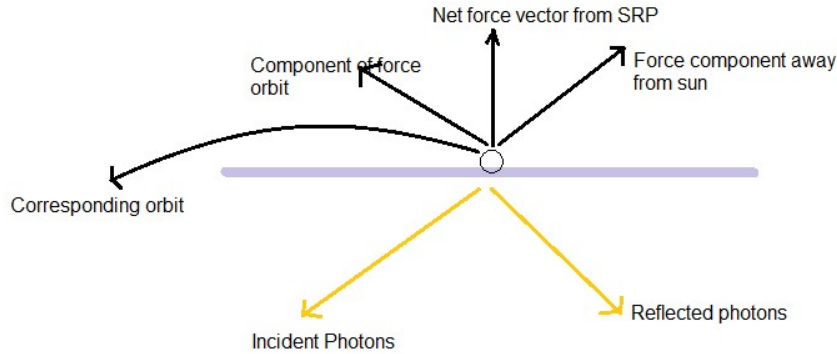


Fig 5.1: Attitude Dynamics of Sail

Fig 5.1 determines the attitude dynamics of the solar sail. Attitude dynamics are extremely essential to reenact the response of the sail to the control forces and other external forces. The standard spinning sail is designed and therefore the standard Newton-Euler equations are extended for the disc spinning sail and afterward the moment of inertia of sail satellite is utilized as the cross-coupling boundary that connects satellite attitude dynamic elements to the other dynamics.

5.1.1 Newton- Euler Equations:

Newton – Euler equation is used to determine the rotational dynamics of the sail. This is extended for the disc spinning sail configuration. The equation is derived and the moment of inertia is further calculated for the solar sail by using this equation.

By Newton – Euler equation the change in the angular momentum is equal to the external torques acting on the sail membrane.

$$dH/dt = N,$$

Where H is the angular momentum and N is the external torque.

$$H = I \times \omega$$

I is the moment of inertia and ω is defined angular rate.

The total angular momentum force for the disc spinning sail is the summation of the angular momentum of the sail body (H_b), the angular momentum of the satellite (H_s), and the angular momentum of the counter system (H_c). I_b is the moment of inertia of sail, I_s and I_c are the moment of inertias of satellite and counter system, respectively. The angular rate between the inertial frame and the satellite body is given by ω_i . For the spinning sail, the counter forces are negligible. Therefore $H_c = 0$. The total angular momentum of the sail is given as

$$H = H_b + H_s$$

$$H = I_b \omega_i + I_s \omega_i$$

$$H = (I_b + I_s) \omega_i$$

Substituting these values in the Newton Euler equation gives the total external torques.

$$dH / dt = N$$

$$N = d/dt (I_b + I_s) \omega_i$$

$$N = (I_b + I_s) \dot{\omega}_i + \omega_i I_s + \omega_i \times (I_b + I_s) \omega_i$$

This equation determines the total external torques acting on the sail. The inertia in the equations is not a constant one and changes when sail gets deployed or when booms move relatively. This shows how the inertia change affects the attitude of the satellite.

5.1.2 Moment of Inertia:

The moment of inertia is an important aspect of the attitude dynamics. For the disc spinning sail, the sail rotates continuously causing the changes in inertia and angular momentum that affect the satellite mechanism. This inertia also gets

changes due to the inertia. For determining the inertia, before and after deployment of the sail are assumed to remain steady. The inertia is the sum of the satellite transport, deployment system, wire booms, stored sail structure, sail mechanism, and sail blasts. The inertia of sail before deployment is given as

$$I = I_b + I_c + I_s$$

Inertia is the product of mass and the square of the distance between the two axes.

$$I = mr^2$$

$$I = [A]^{-1} r^2$$

The matrix A is the transformation matrix, m_{st} is the mass of sail booms.

Since the model proposed have 4 booms the total moment of inertia is given by

$$I = \sum_1^4 \begin{bmatrix} m_{st} d_{xi}^2 & 0 & 0 \\ 0 & m_{st} d_{yi}^2 & 0 \\ 0 & 0 & m_{st} d_{zi}^2 \end{bmatrix}$$

The moment of inertia of deployed sail given as

$$\begin{aligned} I_{\text{deploy}} &= 1/6 m_{\text{sail}} A \\ &= 1/6 (4 m_{ss}) \pi r^2 \\ &= m_{ss} L^2/4 \end{aligned}$$

Where m_{sail} is mass of sail, L is the maximum length of wire boom.

$$\text{Then } I_{\text{sail}} + I_{\text{booms}} = \sum_1^4 \begin{bmatrix} (m_{st} + m_{ss}) d^2 x & 0 & 0 \\ 0 & (m_{st} + m_{ss}) d^2 y & 0 \\ 0 & 0 & (m_{st} + m_{ss}) d^2 z \end{bmatrix}$$

The moment of inertia before and after deployment is substituted in the Newton-Euler equation. Then the inertia acts as an association between the satellite and wire elements. The effects of torques on the sail change the satellite dynamics and acceleration thus changing the moment of inertia. Hence the reaction to

different input torques is different. The cross-coupling dynamics of disc spinning sail are given in Fig 5.2.

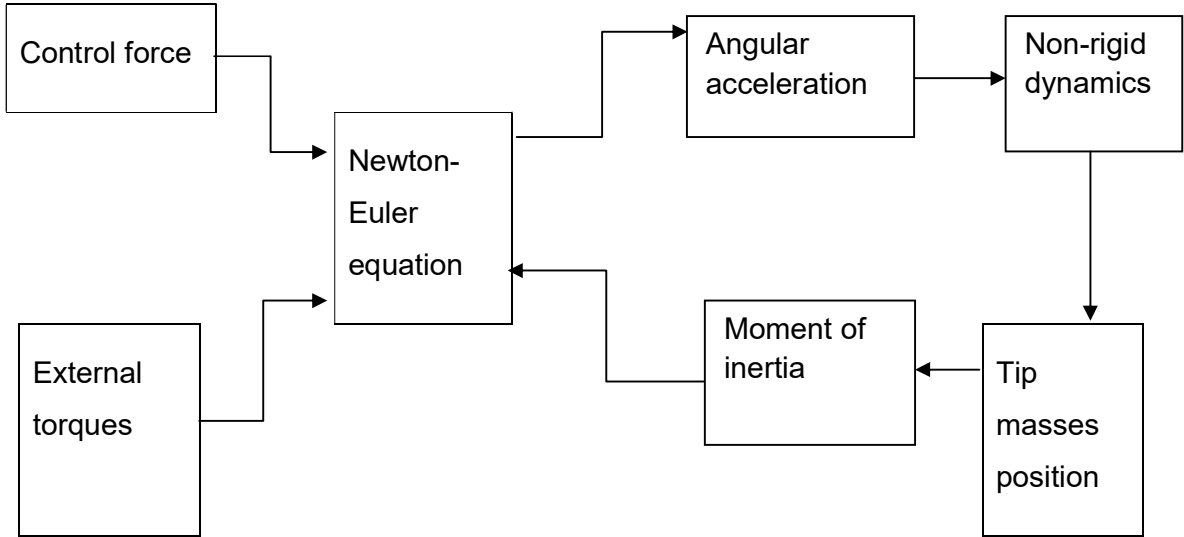


Fig 5.2: Cross-Coupling Dynamics

5.1.3 Disturbance Torques:

Solar sail due to its large membrane possesses various disturbance torques that are present in the outer atmosphere. Due to these torques c_m and c_p offsets are created which affects the sail attitude dynamics. The sail experiences solar thrust in two directions such as tangentially (F_t) and normally (F_n). Therefore, the total thrust force is the sum of these two.

The tangential thrust force is

$$F_t = PA (1-r_o s) \cos \varepsilon \sin \varepsilon$$

The normal thrust force is

$$F_n = PA (1+r_o s) \cos^2 \varepsilon$$

The total solar thrust force is

$$F_s = F_n + F_t$$

Here, P is the solar radiation pressure, A is the projected area of sail, ϵ is the angle between the normal surface of sail and the incident photons and r_o is the reflection parameter.

The total disturbance torque by the spinning satellite is the product of solar thrust force and c_p and c_m offset distance.

$$N_s = r_{\text{com-cop}} \times F_s$$

The sail also possesses the drag force if it is nearer to the earth due to the particles present in the atmosphere. It is given as

$$F_d = mV^2/r = r_d/r A v_{\text{rel}}^2 [\sigma_t + \sigma_n (v_b/v_{\text{rel}})]$$

Where, r_d is the local atmospheric density

A is sail area, v_{rel} is the relative velocity of a satellite to the atmosphere, σ_t , and σ_n are tangential and normal coefficients, v_b is the escape velocity and r is the radius of rotation.

The total disturbance torque due to the drag force is

$$N_d = r_{\text{com-cop}} \times F_d$$

Other disturbances include gravity gradient torques which are lower in higher orbit altitudes is given as

$$N_g = 3\mu\epsilon A^2 / R^3 \frac{I_x}{I_z}$$

The disturbances mentioned are major disturbances affecting the attitude controls. There are several other disturbances in the outer environment but these are negligible as the disturbance is very less compared to the mentioned disturbances. The sail must absorb all these disturbance torques to maintain a proper attitude.

5.2 Orbital Analysis:

Satellite orbital analysis is similar for the solar sails as well as other satellites

using the low propulsion system. The orbit maneuvers are necessary for designing a mission and also for giving the proper sizing to the sail.

5.2.1 Orbits and Trajectories:

The solar sails take much time to reach their desired orbit, changing the orbits by the sail increases the ability in performing different tasks. Therefore, it is essential to optimize the transfer trajectory of the solar sail to reduce the transfer time that helps in exploring the deep space science missions. However, trajectory optimization is not easy to solve, the research regarding this is still in the early stage and is now done by the classical indirect calculus methods but this involves some disadvantages including the difficulty in detecting the optimal condition, the convergence radius, and also this is not possible to detect the position of the solar sail in the initial orbit. Moreover, the minimum time required for positioning the sail in the other orbit can be calculated by using the direct discrete method. It is concluded that the direct collocation method and the pseudospectral methods are used to obtain the higher solution accuracy and also the finite element method is used to determine the position and time taken by the sail. This trajectory optimization can be done with the numerical procedure and implemented further after launching in the space. Generally, transfer trajectory optimization of the sail is determined by the Bolza form, which gives the dynamic constraints, path constraints, and the boundary constraints of the sail. Also, the initial time and terminal time will be calculated.

Solar sails are the propulsion system that helps in changing its orbit. Orbital are controlled by two modes namely earth-centered orbits which decrease its orbit altitude to deorbit or increases its altitude and sun-centered orbits are those which generate a forward force to restrict its direction of speed to move nearer to the sun spirally. With regards to the orbits, usually, most of the earth-centered solar sails are placed in the L1 orbit as this is the nearest orbit to the earth, but a satellite with a large membrane solar sail and desirable shapes also works when they are far away from the sun. However, usually, the L1 orbit is preferable. These satellites also made to move to other planet orbits by placing them in uncentered orbits. Also, sails are made to move to the orbits that are away from the sun using the giant lasers that change the path of the sail from the current orbit and help it to

move to the other orbits. This technology is still in development and not possible with the current technology so this might go to be implemented shortly soon.

5.2.2 Sun-Centered Orbits:

As discussed earlier, there exist two modes. As shown in Fig 5.3, the sail changes its position spirally. As it covers multi targets, it is ideally suited for interplanetary missions. Usually, the sail is influenced by the earth's gravitational influence and if it is placed in the sun-centered orbit. It continuously spins until it reaches its desired planet location and then changes the orbit to reach the planet's sphere of influence. Only large sails are applicable for this mission and a spinning sail of a large surface is capable of performing these types of complex missions.

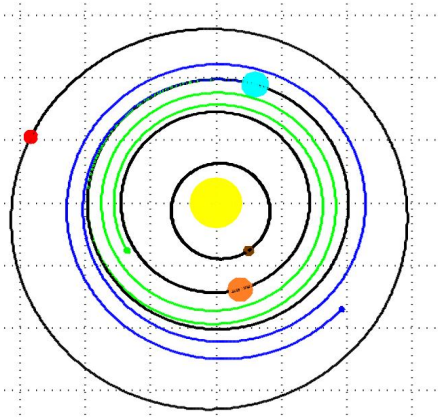


Fig 5.3: Sun-Centered Orbit

Since the sail is not located in the desired position, the sun rays' angle and the solar radiation pressure alters along its path. This sail satellite also increases the orbit altitude by maintaining the optimal angle of the sun. The solar radiation pressure P at a distance of r from the sun's Centre is given as

$$P = P_s \sqrt{(r_{\text{earth}}/r)}$$

Where P_s is the solar radiation pressure at a distance of 1 AU from the sun

r_{earth} is the radius of the orbit of the earth

$$P \text{ is } \propto 1/r$$

Therefore, the solar radiation pressure increases when the sail moves closer to

the sun and vice versa. The disc spinning solar sail is placed at an angle of 35.26 degrees of inclination pointing towards the sun. This mode changes the eccentricity very fast and helps in moving the sail to other planets quickly. The Inclination is very carefully mentioned here unlike the earth-centered sail as the inclination has a large effect on the sail trajectory.

CHAPTER 6

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 folding. 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.

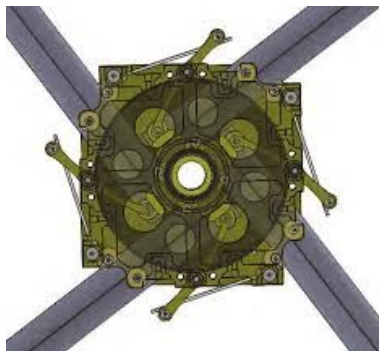


Fig 6.1: Deployment Mechanism

Fig 6.1 describing the deployment mechanism of the sail. In solar sail, there will be two types of mechanisms, active deployment mechanism, and passive deployment mechanism. In an active deployment mechanism, the solar sail and the deployment mechanism system rotate the sail. Here electric motor will be used for the construction and the solar sail is appended to a pulley and so it can deploy the sail slowly and then here tape blasts are attached to sensors and it can produce feedback on a moment of the deployment mechanism. Above the solar sail, the source is connected to a programmed computer that requires controlling and signaling by the electric lines that are connected to the sail where it's rotating.

For the sails having rigid booms and other supporting structures, various difficult

mechanics have to be installed for the proper deployment. For example, in the square sails, folding of the sail involves complexity because of the booms, due to which it requires a larger volume for packing. Initially, the structural members should come out along with the satellite and then the membrane. Usually, electrical motors or some fuel components which give drastic energy are used to deploy the sail. Sail deployment involves a lot of difficulty as using electrical devices might cause the sail to strike inside the object or else using fuel components for rapid opening of sail membrane might be the biggest concern as sometimes leads to the blasting of sail. Sails with booming technology might lead to jamming, buckling, and other issues which cause deployment failure. A coilable design is made and deployed for non-rigid sails usually. For smaller sails, the deployment is not complex as it did not require any high-efficiency electrical motors however large sails involve complexity which leads to the failure of most sails. Therefore, the deployment mechanism used depends on the type of sail and the size of the sail. For instance, IKAROS sail used mechanical devices for the deployment. The required electricity for these mechanical devices will be given by the solar cells, placed on the surface of the sail membrane. Whereas, the technique used in Znamya 2 and Znamya 2.5 was by the use of spacecraft which means the sail gets deployed from the end of the rocket, which is unlike the other techniques as the sail was deployed before launching to orbit. This causes the failure of the sail. So, it is important to place the sail in the desired orbit and then, after it gets into the required position only the sail is made to deploy from the cube-shaped or other shaped sat in which the whole sail is packed.

By considering this, an electrical motor that is charged up to a certain level is installed for the deployment. The motor need not be fully charged as this will be used only for a few seconds. The electrical motor is fixed inside the cube-shaped object and after it gets launched into space and positioned in the desired orbit, the sail is made to deploy from the object, and the rapid opening causes vibration problems to the solar sail. The motor should allow the sail to open slowly, which helps in the prevention of various external vibration disturbances. However, this does not apply to sails of all sizes and shapes, only installed to the shapes with flexible structures and non-rigid sails. Although packing and deployment are only needed for launching the sail, these are the crucial steps involved in the sail.

These are responsible for the failure of a several solar sails.

In this deployment of a solar sail, the centrifugal force from the spin can keep wire booms hardened and unbent. Advantages of wire booms are having simplistic of the development. Here when compared to semi-rigid booms, the rotating booms are used which deploys easily with this mechanism.

6.1. Active Deployment Mechanism:

In the active deployment mechanism, it will use a spin-stabilized solar sail satellite and the deployment component will work on a relative rotating mechanism. The solar sail will be deployed by using an electric motor to deploy the booms by using a pulley that is attached to the motor. In this deployment mechanism, the motor will deploy the sail slowly for the reason to deploy the sail successfully. For deployment by the active deployment mechanism, a motor is connected using the pulley method which helps to compact the wire booms in a certain space that is used to release booms slowly. In these cases, slip rings will be used to produce a connection in between which is required for the deployment system. It is used to supply a solution to the system with the required control and feedback. It is considered and rated by the maximum rotations or total rotation taken. It will send feedback for deploying a large structure sail, here it will be mainly constructed by a stepper motor, brushless motors, or DC brush motors. And here for a circular spinning solar sail, the 2x spinning system is used to deploy the sail. With the help of motors, 6 recalling blades were chosen and 12 jumpers to transfer power between the payload and the sail. This active mechanism, it will limit the angular rate of the system, it will always act and take power from the sail.

In this deployment, a wireless module is placed. Here it is previously programmed to control the rotation of the sail and for supplies. For this there will be no angular rate limit, the wireless module contains its battery power source and processing programs and it is programmed to create that, only during the deployment process. It will provide full control to the deployment. It takes a less complex and low expensive 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 on the active deployment.

6.2 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 which also includes the satellite and other mechanisms so that it fits into the launch vehicle. Packing is the most challenging in designing the sail as it is not only about packing into a small volume but also packing in such a way that the sail has to deploy easily by not damaging the membrane as it is very thin. For, the heliogyro the folding is much simpler as it involves just reeling the strips. These include different techniques in packing a sail structure. One type includes folding the sail membrane to the hub that is the center of the sail. Another type includes folding of the sail in the triangular shape, which is implemented in surrey cube sail, and folding in lines called the Miura-Ori folding pattern. Another common folding includes spiral folding by Guest& Pellegrino technique that is rolling the membrane around hub resulting in a circular shape.

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 and type of the sail and also the materials used for the sail manufacturing. Usually, rigid sails have external structures for giving support, these supports are not flexible which makes them complex while packing and these require different origami techniques with some mechanical supports in the body in which it is packed. For the design, 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. Therefore, non-rigid sails have major advantages when packing while rigid sails involve more complexity.

There are some uniaxial packings in which only one-dimensional packing included z-folding, rolling, and fan folding. This is the packing which was mostly used in uniaxial completion. This packing will be based on the thickness of the sheet of material. In uniaxial compaction, deployment can be carried out simply when compared to biaxial compaction. It is mainly seen in a uniaxial deployment mechanism. This method is not suitable for the solar sail because this method is

not compact. This method was followed by some space satellites which were successfully deployed. In this packing, it will deploy 2 booms from the wings. Biaxial compaction is mainly formed to be compact which is mainly formed from the origami. It describes certain folders that use to provide inner and outer folding for the packing.

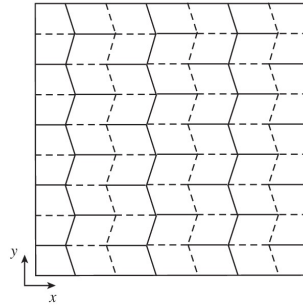


Fig 6.2: Miura-Ori Folding Technique

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 Fig 6.2.



Fig 6.3: Guest and Pellegrino Folding Technique

This folding is mainly forming a solid cylinder folding as shown in Fig 6.3 which is mainly 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. These techniques were also used on Sunjammer, IKAROS, cube sail, nano solar sail, etc.

6.3. Deployment Experiment:

In this deployment experiment, four booms are folded and rolled to fix some

masses near the tip of the fixed folding. The deployment experiment has two stages, when deployment starts in the first stage tip masses will be released to give space to escape the wire booms. Then it will extract the booms in the form of the spinning method. It will open the booms up to stoppers, later stoppers will release the aluminized mylar material from the booms and four booms will be expanded in the form of a square shaped sail, this deployment method is used in IKAROS solar sail.

In this deployment experiment, active deployment mechanism is considered, which works on the support of a running motor that was electrically connected. In this experiment, it took 3 phases to deploy the solar sail. In the first phase, the motor is automatically modified by the software which gives a certain amount of rotation and power. Then in the second phase, the 6 wire booms will be released from the pulley that is connected to the motor. Then in the last phase, aluminized mylar sheet which is folded in the form of the Miura-Ori folding method is connected to the center of a bus and it is released by spins that are connected in between wire booms and the solar sail bus, then the material will be extracted deploying disc spinning sail.

6.3.1 Experimental Setup:

The spin-stabilized disc-shaped sail is designed by the software Catia and then the simulation of the sail by the Ansys. The prototype of the sail is made which includes the packing of sail, attitude control, and deployment of the solar sail. Initially, a prototype of the disc sail of a 15 m radius and spin stabilization is designed with aluminized mylar sheet. Secondly, the sail is packed in a cube-shaped sat in the Miura-Ori and Guest& Pellegrino folding technique. Thirdly, the deployment of the sail is done with the help of the electrical stepper motor which is charged partially. Finally, the attitude control to the sail is given by placing the reflective panels (LCD panels) on all four sides of the sail with the automatic on/off technique such that the alternative sides are on the on mode at the same time other sides are in off mode and vice versa. Spin stabilized sail satellite used is developed by the automatic controlled software, before the start of the experiment. Some analyses are performed on different solar sails by using Ansys software which was constructed by a certain length and then experimenting on

heat flux, deformation, stress, and strain analysis.

Mainly the spin-stabilized solar sail is constructed with 4 wire booms which were made from tape blade material (normally some wire booms are used as those have the low escape reflex). The solar sail is programmed by a software chip Arduino mega which programs the supplies, power supply, and rotating. Here to rotate the solar sail stepper motor is used. This motor can't run without the help of any drivers, transformer, or compensators, so this is connected to the L298 driver which avoids the bad supply and fuses the stepper motor to run. To construct the spin-stabilized solar sail the setup is made and a certain mechanism is used to deploy. Here active deployment mechanism is taken which is easier to construct than the other deployment methods. This mechanism is controlled by a power supply individually.

6.3.2 Outcome:



Fig 6.4: Deployment at 0 sec



Fig 6.5: Deployment at 10 sec



Fig 6.6: Deployment at 28 sec



Fig 6.7: Deployment at 50 sec

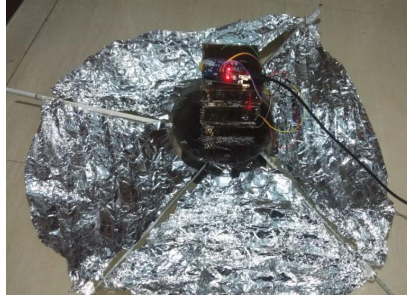


Fig 6.8: Deployment at 90 sec

The outcome seen in Fig 6.4, the solar sail is packed in circular cylindrical folding. At this phase, the time taken is 0 sec.

As seen in Fig 6.5, the solar sail is deploying with the help of an active deployment mechanism and the aluminized mylar sheet was releasing at a time with the wire booms, the time is taken at this deploying form is 10 sec.

As seen in Fig 6.6, the solar sail is under the deploying processes, the time taken at this deploying form is 28 sec.

As seen in Fig 6.7, the solar sail is under deploying process, and the time taken is 50 sec. To stabilize the deployment process, deployment takes place at slow action.

As seen in Fig 6.8, the solar sail is seen to be in the final form of deployment. The time taken to deploy the overall solar sail material is 90 sec for the 1.5 m solar sail.

The sail gets deployed without getting untangled successfully. For a prototype of 1.5 m diameter, it took around 90 sec to deploy completely. The whole model of 175 m^2 will take 4474 sec to deploy completely. This was compared to IKAROS as it was the successful sail launched in the sun-centered orbit and also it is of nearly the same area as the sail designed. IKAROS took 3000 sec to deploy successfully and then comparing both the sails. Sail designed with the active deployment demonstrator is considered to be ideal as it was able to deploy successfully and completely like the IKAROS with both sails taking nearly the same time to deploy completely.

CHAPTER 7

CONCLUSION AND SUMMARY

This work introduced a disc-shaped spin-stabilized solar sail design that can make the satellite positioned in a particular orbit without getting affected by the external disturbances in the space and with less mechanical complexity. This also helps in making the packing and deployment uncomplicated. This mission has the advantages of both spinning sails as well as the disc-shaped sail. A disc sail helps in using the flexible booms instead of steady structures for the support whereas the spinning sail reduces the offset distance of c_m and c_p . Spinning satellite is more resistant to the external disturbance torques, which leads to misalignment of the center of mass and the center of pressure than the non-rotating sails and these sails also produce continual centrifugal force, that helps in reducing the billowing of the sail and making it possible to use the wire booms instead of the rigid booms which are difficult to deploy.

With the disc sail, the sail is packed inside the cube-shaped satellite of 6U with the folding technique such as Miura-Ori technique and Guest & Pellegrino folding around the stepper motor that is easily deployable after it is launched into space. The attitude control is also important and is achieved by the installing of the lightweight flexible LCD panels on all four sides of the sail which helps in the packing and deployment of the sail and the proper attitude controlling of the sail. The circular-shaped spin-stabilized sail is designed and preferred to be launched in the sun-centered orbits, as it will not only used for the launching of satellites in low earth orbits but also helps for interplanetary missions in the future.

7.1 Design and Deployment Evaluation:

The conventional spinning sail of disc-shaped is designed and then the attitude controlling is given to the sail. The structural dynamics are investigated by the thermo-structural analysis. Newton- Euler equations are used for determining the moment of inertia and the torques due to disturbance forces on the sail are calculated and then the attitude dynamics described. The deployment demonstration was built practically using the active deployment mechanism and the deployed membrane at various intervals of time is stated.

7.2 Advantages over Other Sails:

There are numerous advantages of using a spin-stabilized disc-shaped solar sail such as

- Very simple to keep the satellite in a certain position in the orbit in which it is launched.
- These satellites also resist the small perturbing forces present in space.
- The circular-shaped satellite is packed easily and does not require any complex mechanics as it does not include any rigid structures or rigid booms for supporting the structure.
- The deployment is done by an active deployment mechanism which was also made easy due to the folding technique used here and deployment also did not involve any difficult mechanisms.
- As the spin stabilization is used, this could probably produce more acceleration compared to other sails that also helps in moving the sail to other planet orbits in less time.
- Solar sails do not require any external energy, here along with the attitude controls which are made using the LCD panels. These make use of solar energy keeping the lifespan of the sail much longer.

7.3 Future Implications:

Solar sails have the ability to deploy huge sail membranes in space and its 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 made to move 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 be stored, 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 also 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 here 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 Fig 7.1. So that the sail will be directed towards the desired direction and also this 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. For this, the sail needed to be fitted in the launch vehicle and able to produce more acceleration. This work provides a design that can fit in a small volume and producing more acceleration which is essential in future missions.

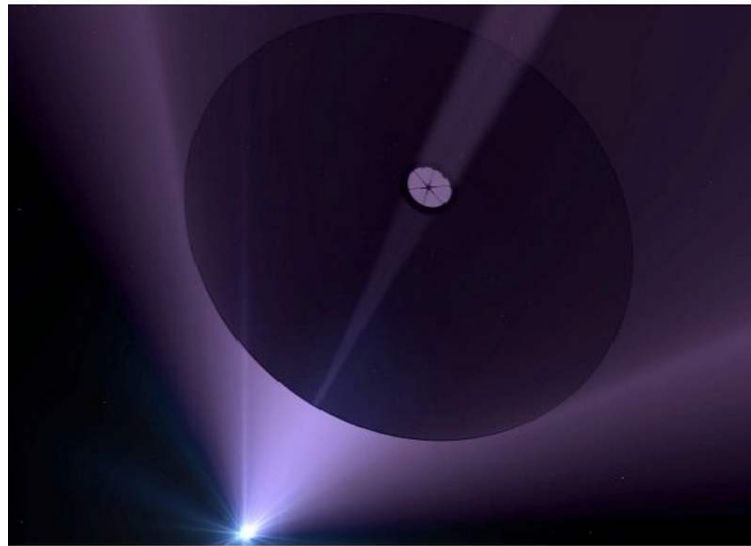


Fig 7.1: Sail Movement with Laser Propulsion

REFERENCES

- [1] Colin R. McInnes. "Passive Control of Displaced Solar Sail Orbits" ,1998, <https://doi.org/10.2514/2.4334>
- [2] McInnes, Colin R., Malcolm MacDonald, Vassilis Angelopolous, and David Alexander,"GEOSAIL: Exploring the Geomagnetic Tail Using a Small Solar Sail", 2001, <https://doi.org/10.2514/2.3727>
- [3] Gerald Falbel, Prof Jordi Puig-suari, Andrzej Peczalski,"Sun oriented and powered, 3 axis and spin stabilized cube sats",2002, DOI: [10.1109/AERO.2002.1036864](https://doi.org/10.1109/AERO.2002.1036864)
- [4] David M.Murphy, Thomas W.Murphey," Scalable Solar Sail Subsystem Design Considerations", 2002, DOI: [10.2514/2.3975](https://doi.org/10.2514/2.3975)
- [5]Liepold, Eiden, Garner, Herbeck, Kassing, Niederstadt, Kruger, Pagel, Seboldt, Schoppinger, Sickinger, Unckenbold,"Solar sail technology development and demonstration",2003,[https://doi.org/10.1016/S0094-5765\(02\)00171-6](https://doi.org/10.1016/S0094-5765(02)00171-6)
- [6]David M. Murphy, Thomas W. Murphey, Paul A. Gierow. "Scalable Solar-Sail Subsystem Design Concept" , 2003, DOI: [10.2514/2.3975](https://doi.org/10.2514/2.3975)
- [7]David Edwards, Mary Hovater, Whitney Hubbs, George Wertz, William Hollerman, Perry Gray. "Characterization of Candidate Solar Sail Material Exposed to Space Environmental Effects" , 2004, DOI: [10.2514/6.2004-1085](https://doi.org/10.2514/6.2004-1085)
- [8]Bernd Dychtwald," Optimal Solar Sail Trajectories for Missions to the Outer Solar System", 2005, DOI: [10.2514/1.13301](https://doi.org/10.2514/1.13301)
- [9] Vaios Lappas, Manfred Leipold, Peter Falkner, H Fichtner, S. Kraft. "Interstellar Heliopause Probe: System Design of a Solar Sail Mission to 200 AU", 2005, <https://doi.org/10.2514/6.2005-6084>
- [10] Macdonald, Malcolm, Gareth Hughes, Colin McInnes, Aleksander Lyngvi, Peter Falkner, Alessandro Atzei. "Solar Polar Orbiter: A Solar Sail Technology Reference Study", 2006, <https://doi.org/10.2514/1.16408>
- [11]Hughes, Gareth W., Malcolm Macdonald, Colin R. McInnes, Alessandro Atzei, and Peter Falkner. "Sample Return from Mercury and Other Terrestrial Planets Using Solar Sail Propulsion", DOI: [10.2514/1.15889](https://doi.org/10.2514/1.15889)
- [12]Bong Wie, David Murphy," Solar-Sail Attitude Control Design for a Sail Flight ValidationMission", 2007<https://doi.org/10.2514/2.3727>
- [13] L. Rios-Reyes and D. J. Scheeres ,"Solar-Sail Navigation: Estimation of Force, Moments, and Optical Parameters", <https://doi.org/10.2514/1.24340>
- [14]Bong Wie," Solar Sail Attitude Control and Dynamics, Part 1" 2008 DOI: [10.2514/1.11134](https://doi.org/10.2514/1.11134)
- [14] Shahid Baig, Colin R. McInnes. "Artificial ThreeBody Equilibria for Hybrid Low-Thrust Propulsion", 2008, <https://doi.org/10.2514/1.36125>
- [15]Vaios Lappas, Nasir Adeli, Matthew Perron," CubeSail: A low cost CubeSat based solar sail demonstration mission", 2011, <https://doi.org/10.1016/j.asr.2011.05.033>
- [16]Ryu Funase, Yoji Shnirasawa, Yuga Mimasu, Jun'ichiro Kawaguchi," On-orbit verification of fuel-free attitude control system for spinning solar sail utilizing solar

- radiation pressure", 2011, <https://doi.org/10.1016/j.asr.2011.02.022>
- [17] Les Johnson, "NanoSail-D: A solar sail demonstration mission", 2011, <https://doi.org/10.1016/j.actaastro.2010.02.008>
- [18] Malcolm Macdonald, Colin McInnes, "Solar sail science mission applications and advancement", 2011, <https://doi.org/10.1016/j.asr.2011.03.018> [19] Les Johnson, Roy Young, Edward Montgomery, Dean Alhorn, "Status of solar sail technology within NASA", 2011, <https://doi.org/10.1016/j.asr.2010.12.011>
- [20] Matteo Ceriotti, Colin R. McInnes. "Generation of Optimal Trajectories for Earth Hybrid Pole Sitters", 2011, DOI: [10.2514/1.50935](https://doi.org/10.2514/1.50935)
- [21] David Murphy, Michael McEachen, Brian Macy and James Gaspar, "Demonstration of a 20-m Solar Sail System", 2012 <https://doi.org/10.2514/6.2005-2126>
- [22] Tsuda, Mori, Funase, Sawada, Yamamoto, Saiki, Endo, Kawaguchi, "Achievement of IKAROS — Japanese deep space solar sail demonstration mission", 2013, <https://doi.org/10.1016/j.actaastro.2012.03.032>
- [23] Yuichi Tsuda, Takana Saiki, Ryu Funase, Yuya Mimasu, "Generalized Attitude Model for Spinning Solar Sail Spacecraft", 2013. <https://doi.org/10.2514/1.59516>
- [24] Jeannette Heiligers, Ben Diedrich, Billy Derbes, Colin R. McInnes, "Sunjammer: Preliminary End-to-End Mission Design", 2014, DOI: [10.2514/6.2014-4127](https://doi.org/10.2514/6.2014-4127)
- [25] W. Keats Wilkie, Jerry E. Warren, Jer-Nan Juang, Robert G. Bryant, "Heliogyro Solar Sail Research at NASA", 2014, DOI: [10.1007/978-3-642-34907-2_39](https://doi.org/10.1007/978-3-642-34907-2_39)
- [26] Liu, J., N. Cui, F. Shen, and S. Rong. "Nonlinear static analysis-based thrust for solar sail", 2015, <https://doi.org/10.1177/0954410014527921>
- [27] Alessandro Peloni, Daniele Barbera, Susanna Laurenzi, Christian Circi. "Dynamic and Structural Performances of a New Sailcraft Concept for Interplanetary Missions" , 2015, <https://doi.org/10.1155/2015/714371>
- [28] Junshan Mu, Shengping Gong, Pengbin Ma, Junfeng Li. "Dynamics and control of flexible spinning solar sails under reflectivity modulation" , 2015, DOI: [10.1016/j.asr.2015.07.028](https://doi.org/10.1016/j.asr.2015.07.028)
- [29] Les Johnson, Alex R. Sobey, Kevin Sykes. "Solar Sail Propulsion for Interplanetary Cubesats" , 2015, <https://doi.org/10.2514/6.2015-3895>
- [30] Fan Shen, Siyuan Rong, Hualan Zhang, Fuun Peng, Naigang Cui, "Correction and adjusting for the deformation on solar sail", 2016, <https://doi.org/10.1007/s12567-016-0128-2>
- [31] Bo Fu, Evan Sperber, Fidelis Eke, "Solar sail technology—A state of the art review", 2016, <https://doi.org/10.1016/j.paerosci.2016.07.001>
- [32] Giovanni Mengali, Alessandro A. Quarta. "Heliocentric trajectory analysis of Sun-pointing smart dust with electrochromic control", 2016, <https://doi.org/10.1016/j.asr.2015.12.017>
- [33] Kenshiro Oguri, Takumi Kudo, Ryu Funase. "Design Criteria of Reflectivity Control System under Uncertainty in Sail Property for Maneuverability Requirement of Spinning Solar Sail", 2016, <https://doi.org/10.2514/6.2016-5674>
- [34] Mark L. McConnell. "High energy polarimetry of prompt GRB emission", 2017,

<https://doi.org/10.1016/j.newar.2016.11.001>

[35]Junji Kikuchi, Toshihiro Chujo, Yoji Shirasawa, Osamu Mori. "Windmill Torque Estimation of Spin-type Solar Power Sail with Shape Control" ,2016,

<https://doi.org/10.2514/6.2016-1218>

[36]Luisa Boni, Alessandro A.Quarta, Giovanni Mengali," Thermal-structural analysis of a square solar sail", 2018,

<https://doi.org/10.1016/j.actaastro.2018.03.037>

[37] Yufei Guo, Dongzhu Feng, Xin Wang, Cong Li, Yunzhao Liu, " The Earth-Mars Transfer Trajectory Optimization of Solar Sail Based on - Adaptive Pseudospectral Method " ,2018, <https://doi.org/10.1155/2018/6916848>

[38] Shengping Gong, Malcolm Macdonald. "Review on solar sail technology" , Astrodynamics, 2019, DOI: [10.1007/s42064-019-0038-x](https://doi.org/10.1007/s42064-019-0038-x)

[39]Yuki Takao, Osamu Mori, Jun'ichiro Kawaguchi. "Self-excited oscillation of spinning solar sails utilizing solar radiation pressure" , 2019,

<https://doi.org/10.1007/s42064-018-0047-4>

[40]Xiyao Huang, Xiangyuan Zeng, Christian Circi, Giovanni Vulpetti, Dong Qiao," Analysis of the solar sail deformation based on the point cloud method",2020,

<https://doi.org/10.1016/j.asr.2020.05.008>

[41]Patric Seefeldt, Jan Thimo Grundmann, Martin Hillebrandt, Martin Zander. "Performance analysis and mission applications of a new solar sail concept based on crossed booms with tip deployed membranes", 2020,

<https://doi.org/10.1016/j.asr.2020.10.001>

[42]Jose E.Morales, Jongrae Kim,Robert R.Richardson," Gyroless Spin-Stabilization Controller and Deorbiting Algorithm for CubeSats, 2020

,<https://doi.org/10.1007/s42405-020-00311-5>