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DESIGN AND TESTING OF A SOLAR SAIL DEPLOYMENT UNIT FOR A SOLAR SAILING NANOSATELLITE

Mr. Rohit.D.Patil[a],
Mr. Roven Pinto[b], Mr. Vaibhav Wanere[c], Mr. Juber Shaikh[d], Ms. Chaitra Shet[e], Ms. Tanaya Bapat[f], Ms. Mansi Kabade[g], Ms. Pravin Londhe[h]

[a] *College of Engineering Pune, India, rohitshambhu@gmail.com*
[b] *College of Engineering, Pune, India, pintor15.mech@coep.ac.in*
[c] *College of Engineering Pune, India, wanerevb17.mech@coep.ac.in*
[d] *College of Engineering, Pune, India, shaikhjf17.mech@coep.ac.in*
[e] *College of Engineering, Pune, India, shetcs18.mech@coep.ac.in*
[f] *College of Engineering, Pune, India, bapattd18.mech@coep.ac.in*
[g] *College of Engineering Pune, India, kabademm15.mech@coep.ac.in*
[h] *College of Engineering Pune, India, londheps15.mech@coep.ac.in*

Abstract

The paper presents the design and testing of a solar sail deployment unit used in COEPSAT-2, a nanosatellite being developed by students of College of Engineering, Pune (COEP) which aims to demonstrate orbit manoeuvring using a solar sail while characterizing the charged particle density in space. The solar sail used is an aluminium deposited thin polymer film of area 40 metre-square. The large size of the solar sail creates the requirement for a system to store and deploy it without damage. The sail deployment unit of COEPSAT-2 has a deployer section that contains four booms coiled around a spindle driven by a stepper motor, and a storage unit consisting of four quadrants of the sail wound around a spindle. A novel feature is incorporated that provides the ability to couple the two spindles when required. Guide rollers are used in the deployer to direct the booms along a confined path while compressing rollers through springs provide the force to prevent blossoming. Curved slots have been provided in the deployer to maintain tangential contact between the compressing rollers and booms as the booms are deployed. Four different cross-section for the sail supporting structure, booms were analysed for strength, mass, vibrations. The selection of a novel 'S' profile is presented in the paper. Criteria such as the number of creases, storage design, and packing efficiency were evaluated for various folding patterns which led to the selection of the single-z folding pattern. The storage unit was designed and optimized for minimum size of the spindle which led to an assembled spindle design instead of a singular part. This prevents the use of fasteners for the attachment of sail to storage spindle which simplifies the assembly process. Full scale testing of the solar sail unit is enabled by an indigenously developed test set-up. Review of other such test setups and study of feasibility of the methods suggested therein are also presented here. The test setup enabled to create a low friction deployment platform and minimize the effect of gravity on sail and boom during deployment. This was achieved by using Teflon sheets and fixtures for supporting booms. The test bed was designed considering modularity for easy assembly and access to different parts of the test bed for adjustments. This paper serves to enhance the present knowledge in solar sail deployment systems and to introduce a newly developed system for use in the aforesaid satellite mission.
Keywords: Solar sail, Deployment Unit, COEPSAT-2, Deployer, Boom, Test bed

Acronyms/Abbreviations

COEP: College Of Engineering Pune
CSAT: COEP Satellite
PSLV: Polar Satellite Launch Vehicle
ISRO: Indian Space Research Organization
COEPSAT: COEP Satellite
IKAROS: Interplanetary Kite-craft Accelerated by Radiation of Sun
JAXA: Japan Aerospace Exploration Agency
NASA: National Aeronautical and Space Association
TRAC: Triangular Rollable And Collapsible

1. Introduction

COEPSAT-2 is the second satellite mission of the student team CSAT of COEP. The first satellite 'SWAYAM' was launched successfully on 22nd June 2016 on-board ISRO's PSLV C-34. The satellite completed all the mission objectives during its life time. The scientific objective of the nanosatellite COEPSAT-2 is to demonstrate orbit manoeuvring using solar sail. Besides, the utility of the satellite is to characterize and model the protons in the upper ionosphere. The large area of the solar sail in comparison to the cross-sectional area of the satellite creates an obvious requirement of a system to stow and deploy the sail without any damage. The 'Solar Sail Deployment Unit', which is designed for the above requirement is an assembly of the Deployer and the Storage. Deployer is a mechanism for sail deployment while Storage is where the sail is stowed.

Solar sailing has currently become a popular passive propulsion technique for orbit maneuvering with IKAROS being the first solar sailing spacecraft launched by JAXA in 2010. Other missions include NanoSail-D1, NanoSail-D2 launched by NASA. Lightsail-2 launched by Planetary Society in 2019 successfully demonstrated solar sailing. Lack of detailed literature on the deployment and stowing mechanism of solar sail, and on the testing procedure often creates a gap between the concept level understanding and the implementation of novel ideas such as solar sailing. The paper aims to bridge the gap and motivate further solar sailing missions by explaining the design and testing procedure for sail deployment unit for a nanosatellite. The paper presents the unit as a module which could be used for satellite missions with different payloads, by making appropriate changes.

1.1 Solar sail

A solar sail is a thin and highly reflective film made of a polymer substrate with Vapour Deposited Aluminium (VDA) coating on one side. When solar radiation strikes the surface of the sail, it gets reflected. This results in a momentum transfer which develops a thrust on the satellite. Owing to constraints of space and mass minimization, a sail of minimal thickness is desired. Solar sail with aluminium layer thickness ranging from 0.025 to 1 micron and net thickness ranging from 5 to 15 microns are preferred for propulsion. Proposed area of the sail for COEPSAT-2 is 40 m^2. This sail area with a mass budget of 8.5 kg gives a characteristic acceleration of 0.3529 mm/s^2.The square-shaped sail is divided into four equal triangular quadrants, each of dimensions 4.47 × 4.47 × 6.32 m. From literature studies and by comparing different materials, aluminized Mylar® [1] and aluminized Kapton® [2] are found to suffice the need.

1.2 Background

Development of the deployment system is a crucial aspect of a solar sailing mission. This system for the ESA funded project 'Deployable Gossamer Sail for Deorbiting' [3] consisted of CFRP booms, used as deployable supporting structure for sail. The booms are coiled around a spindle driven by a BLDC motor. The z- folded sail of 25 m^2 area is wrapped around sail spindle of the deployment mechanism. Fig below shows the design.

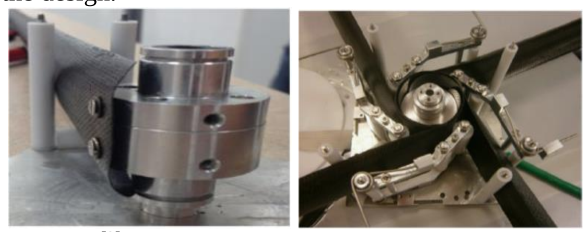

Fig. 1.[3] Boom root attachment to spindle (left) and boom deployer mechanism (right)

In its attempt to develop solar sail technology, NASA's In-Space Propulsion Technology Program (ISP) had given contract to ATK Space Systems, for System Design/Integration of a ground demonstration of a Solar sail mission. The Scalable Square Solar Sail Team (S^4 Team) [4] used the technique of rolling the folded sail on a spool for deployment of a 10- meter sail.

Fig. 2.[4] Sail stowed on a deployment spool

Lightsail-1[5], project of Planetary society demonstrated solar sailing. It used double z-fold and wedge shaped storage for each quadrant of a 32 m^2 square sail. TRAC booms (Fig No. 3) made of two Elgiloy metal strips were used. The boom deployer (Fig No. 4) incorporated a cantilever flat spring to provide a normal force to first collapse the boom into its pinched configuration and then to force the boom to roll around the spindle. The literature survey laid the foundation for the work presented herein.

Fig. 3.[5] TRAC boom

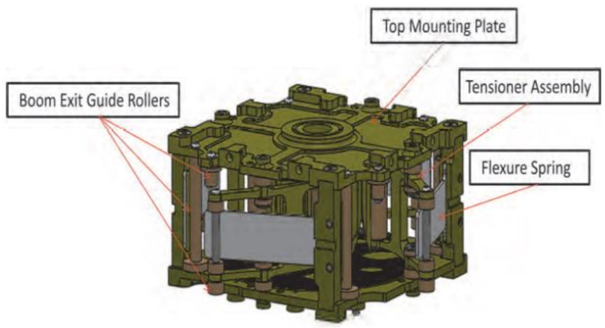

Fig. 4.[5] The deployer assembly

The present work concentrate on solving the practical difficulties in implementing the concepts as discussed in introduction and background. Features like the coupling ring, intermediate plates, assembled storage spindle are the solutions to some of the challenges.
The following section would explain the deployment mechanism and the third section would provide details to the stowing mechanism. The testing procedure and the set-up design would be covered in fifth section.

2. Solar Sail Deployment Mechanism

The mechanism includes Booms and Deployer.

2.1 Booms

Booms are components with a characteristic profile that are used for deployments in space systems. Here the booms are to be used to deploy a solar sail and hold it taut after its deployment. To deploy 40 m^2 sail, 4 booms each of length 4.47 m are used. The four cross-sections being considered are:

- Triangular Rollable And Collapsible [9](TRAC)
- Lenticular[6]
- S shaped cross-section
- C shaped cross-section[7]

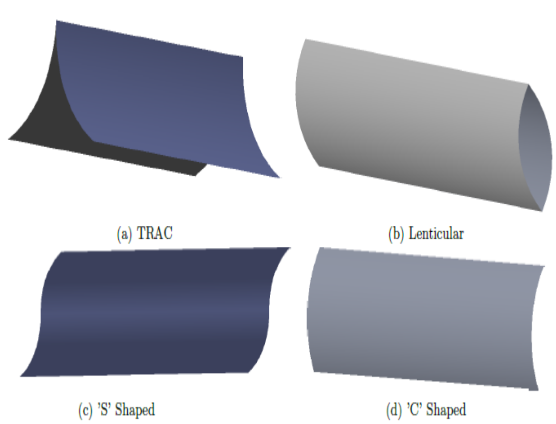

Fig. 5. Type of boom cross section

The design of the boom involves the following stages:

- Study of the forces acting on the boom during and after deployment
- Determination of the magnitude and direction of the forces acting on the boom through experimentation
- Selection of a cross-section for the boom by comparison of required parameters including buckling stiffness, bending strength, total mass and packing efficiency and the initial lag during change of orientation of Sail.
- Determination of the dimensions of the selected cross section

2.1.1 The 'S' profile

The 'C' profile which is the most common and used for tape springs, provide a self-locking feature during bending in one direction only. The same can be seen from the moment vs degree of rotation graph below.

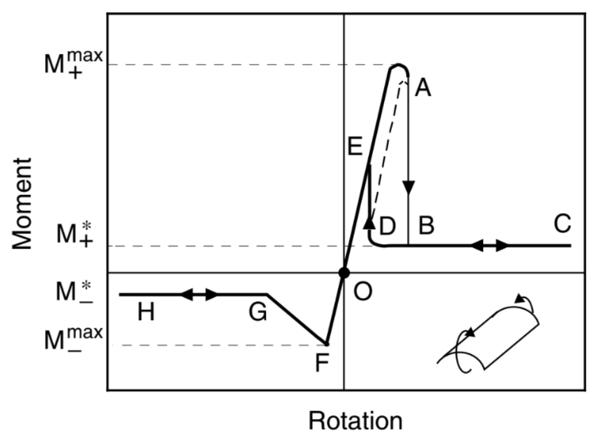

Fig. 6. [8] Systematic M-ϴ relationship for straight tape spring

Thus, 'C' profile can not sustain forces in the other direction i.e in same sense of bending. TRAC and lenticular avoid the above disadvantage by using two 'C' profile joined over edges. 'S' profile uses two 'C' profile joined over edges but in opposite sense as shown. The 'S' boom is superior to the TRAC and lenticular in terms of manufacturibility, end point lag and vibrationn due to satellite rotations as explained below. Thus, 'S' profile is selected.

The four profiles shown in fig. no. 1 were studied and analysed on the basis of their strength, manufacturability and packing efficiency. The orientations of COEPSAT-2[17] demands the booms to sustain a 90^0 rotation in 120 seconds. The boom end lag and the amplitude and decay time of the vibrations of boom after 120 seconds was simulated for all profiles as shown in below figures.

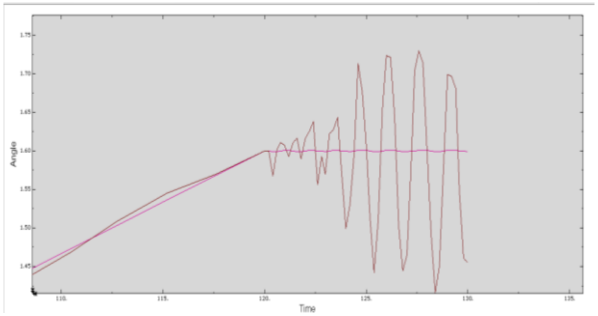

Fig. 7a. Final oscillation after 120 seconds for 'C' boom

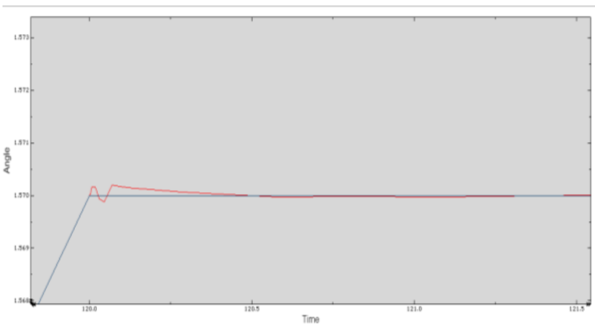

Fig. 7b. Final oscillation after 120 seconds for 'S' boom

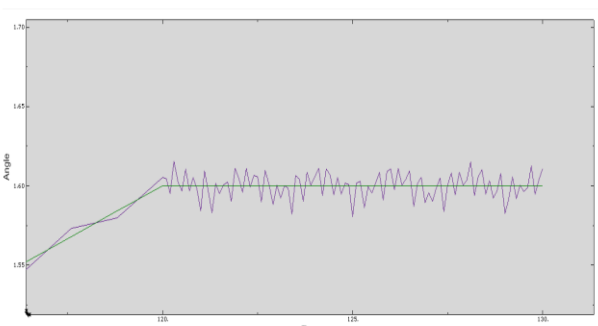

Fig. 7c. Final oscillation after 120 seconds for 'TRAC' boom

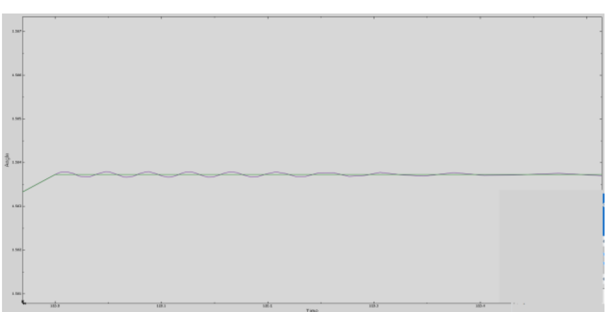
Fig. 7d. Final oscillation after 120 seconds for 'Lenticular' boom

The above graphs shows the vibrational stability of 'S' profile over the other three options. The required buckling and bending strength with the minimum mass constraint can be achieved by using composite material such as glass fibre or carbon fibre. Factors such as stress relaxation and manufacturing difficulties were also studied. [10][11][12][13]

2.2 Deployer

The basic function of the deployer is to deploy the 40 m^2 solar sail. This is achieved with the help of boom as explained in section 2.1. Assembly of the deployer is as shown in figure.

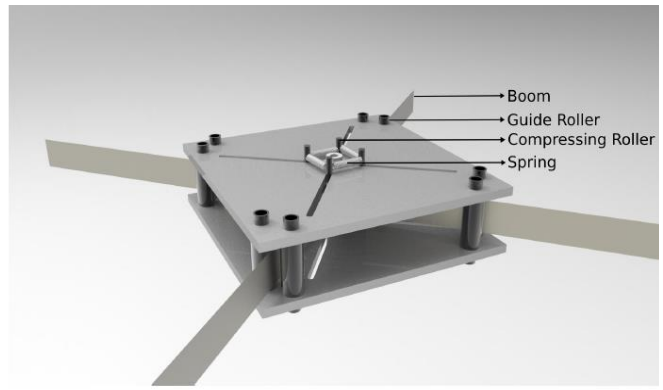

Fig. 8. Deployer

2.2.1 Construction

2.2.1.1 Spindle

It is the component attached to a motor which aids in the uncoiling of booms. For the attachment of the booms, curvilinear slots of appropriate size are made on the spindle. The slots are made in such a way that the booms, after connecting to the spindle, remain tangential to it. This tangential arrangement of the booms ensures maximum transfer of force for deployment. The spindle has a D shaped groove at the motor connection side of the spindle to ensure proper fitting of the D shaped motor shaft into the spindle without any slipping. The spindle is made of Aluminium with the spindle diameter of 30 mm. The lower limit to the spindle diameter was determined from the rolling radius constraint for minimum strain energy in the stowed boom. Assuming off-the-shelf tape spring ('C' profile) as the boom, the minimum strain energy condition requires the rolling radius to be equal to the radius of curvature of 'C' profile used. [7]

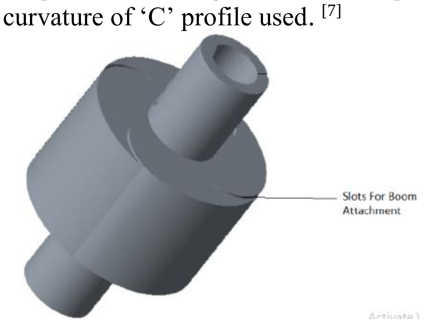

Fig. 9. Spindle

2.2.1.2 Guide rollers

The booms need to be deployed along a confined path which is provided by the guide rollers. These are the rollers placed at the corners to direct the boom accordingly. Eight rollers are used, two for each boom. The distance between the two rollers is not equal to the tensed thickness of the booms, but slightly more than that. The friction force will be considerably high if the spacing between the rollers is just equal to the boom thickness. Also, the upper limit to the distance between them is set by its function of guided deployment. Usually, this distance is equal to the relaxed cross-sectional thickness of booms. Teflon tubes are used to reduce the friction between the boom and roller.

2.2.1.3 Compressing rollers

Stowed booms have a natural tendency for blossoming [14], i.e. the booms tend to increase their radius of coiling on their own on account of the stored strain energy, creating a gap between the central spindle and the inner roll. In order to prevent blossoming, these rollers are positioned around the periphery of the coiled booms such that each roller is at an angle of 90^0 to the adjacent ones. The movement of compressing rollers takes place along the slots provided. Springs will be used to provide the necessary radial force to the compression rollers. They are used on both the sides, upper and lower, to provide uniform compressing force.

2.2.1.4 Springs

Springs provide the necessary compressive force to the compressing rollers. It is designed on the basis of the maximum and minimum coil radius of boom and the necessary force to prevent blossoming. Compressive forces on booms may cause boom slip, resulting into blossoming. Spring should provide sufficient force to prevent this event.

2.2.1.5 Plates

The deployment mechanism is fitted between two square plates. The dimensions of the plates are 160 × 160 × 5 mm. The eight holes at the corners are provided for guide rollers. Slots are made in the plates for the movement of compressing rollers. The compressing rollers should always be tangential to the deploying boom, which requires a curved trajectory of the compressing rollers as the boom get deployed (curved slots not shown in fig. 8.). The curved slots on plates would ensure the tangential contact between the booms and rollers.

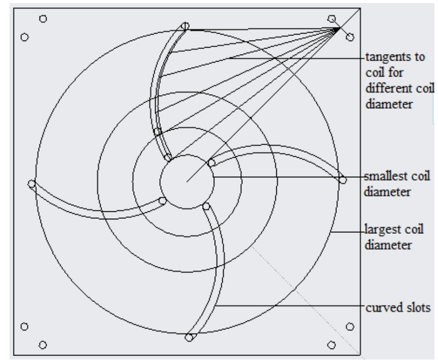

Fig. 10. Deployer plate

2.2.1.6 Bearings

Two bearings are used, one on the upper side and the other on the lower side of the spindle to provide smooth motion between the spindle and the plate.

2.2.2 Working

The deployer stows coiled booms that have high strain energy stored in them. When the spindle rotates, the booms are pushed ahead, which enables the booms to uncoil out of the deployer. The springs provide a radially inward force to the compressing rollers, keeping the radius of coiling as low as possible at all stages. The deployment of the booms continues as the motor is rotated further.

The free ends of the booms are attached to the solar sail with the help of springs. Due to temperature variation, relative expansion takes place between the sail and boom which is compensated by the springs. Solar sail quadrants stowed in the sail storage get pulled out by the booms. Each solar sail quadrant being pulled out gets unfurled as it comes out. It is necessary to provide controlled deployment of booms in order to prevent any damage to the sail. Controlled deployment is achieved using a stepper motor which provides additional safety by rotating in short steps. The process of unfurling continues till the booms are deployed completely.

3. Sail stowing mechanism

The solar sail is divided in four triangular quadrants, each wrapped around the sail spindle. The quadrants has to be folded in a systematic pattern to ensure easy stowing in the storage and safety during the deployment process.

3.1 Folding pattern

Different folding patterns were studied. These includes:

- Double-z folding pattern[5] (Fig. 11a)
- Single-z folding pattern with creases parallel to hypotenuse of the quadrant (Fig. 11b)

- Single-z folding pattern with creases perpendicular to hypotenuse of the quadrant (Fig. 11c)
- Leaf folding pattern[15] (Fig .11d)

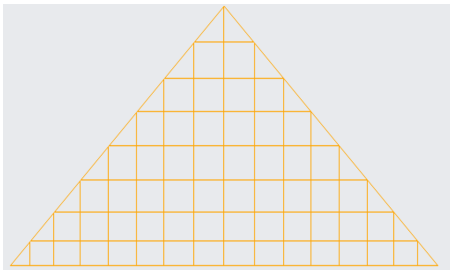

Fig. 11a

Fig. 11b

Fig. 11c

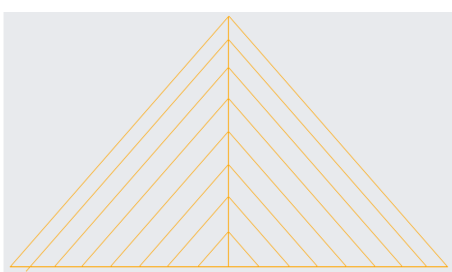

Fig. 11d

3.1.1 Leaf folding pattern

The folding patterns mentioned in section 3.1 were analysed and compared on the basis of the following points:

- Storage Design Complexity
- Height of the storage
- The maximum capacity of the storage
- Creasing Indicator (CI)
- Deployment process

The folding pattern decides the storage configuration. Double-z folding pattern requires compartment based storage design while Single-z pattern requires spindle based design. Space available in spindle based configuration is larger, as reflected from the maximum storage capacities calculated for both. Assuming 100% packing efficiency of sail, the storage capacity of compartment based storage is 45 m^2 (sail thickness 10 microns) and it is 77 m^2 for spindle based storage.

The effect of creases on sail performance and strength is a complex function of the sail thickness, optical properties, operating conditions and folding pattern. These adverse effects increase with the total crease length. CI is a measure of the total length of crease lines on a sail membrane divided by the area of the membrane.

$$CI = (\text{Total crease length}) / (\text{Membrane area}) \quad (1)$$

It can be seen from fig. 11 that CI for single z pattern is nearly 50% lower than that for double-z pattern.

Among the single-z pattern, leaf pattern provides tha advantage of having the strip length after folding equal to the side length of the quadrant (Fig. 11d and fig. 12), unlike other single-z patterns. This permits the deployer and storage spindles to be coupled if required. From the above analysis, 'leaf' pattern was selected for folding and stowing of sail in COEPSAT-2.

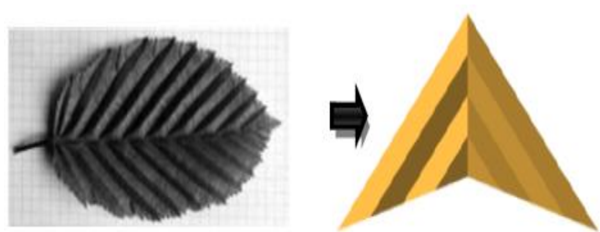

Fig. 12. Leaf folding pattern [15]

3.2 Sail storage

Storage ensures proper stowing of the sail in the satellite. As mentioned in section 3.1.1 folding pattern directs the design of storage. Due to the ease of stowing and higher sail stowing capacity spindle based design with single-z folding pattern (leaf pattern) was selected. Fig. 13 shows the assembly of the sail storage.

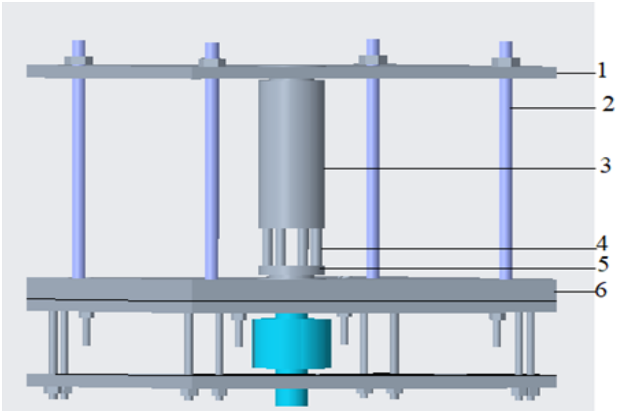

Fig. 13. Sail Storage (front view)

3.2.1 Construction

3.2.1.1 Spindle

The sail after being folded in leaf pattern, is rolled around the spindle. In order to increase the sail stowing capacity or to maximize the available volume for sail storage the spindle was made as an assembly, with two parts. One of it had protrusions (labelled 4, 5 in fig. 13) while the other had recess (labelled 3 in fig. 13). This feature also helped in eliminating fasteners for the attachment of sail to the storage.

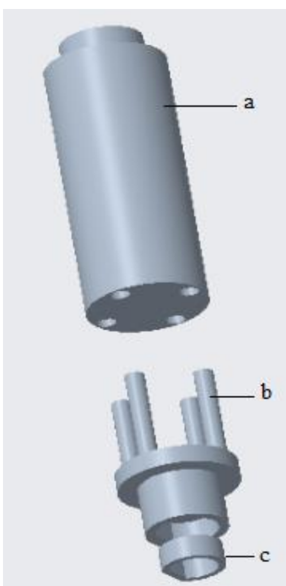

Fig. 14. Storage Spindle assembly

a: Upper Spindle of Storage
b: Lower Spindle of Storage
c: Coupling ring

3.2.1.2 Bearings

Two bearings are used to hold the spindle between the top and bottom plates.

3.2.1.3 Plates

Top (labelled 1 in fig. 13) and bottom plates (labelled 6 in fig. 13) hold the spindle with the help of bearings. To maintain the integrity of the storage, four bolts are used to hold the plates. The bolts are covered with Teflon tubes to prevent damage to sail during deployment.

3.2.2 Working

The sail end to be attached to storage is provided with greater thickness than the rest of the sail for increasing the strength in critical section. The end section is provided with a rivet with the help of which sail quadrant is attached on the spindle. The protrusions of the lower spindle fit in the rivets of the sail end. For stowing the sail, the deployer and storage spindle can be coupled, as explained in section 4. Thus the sail is wound around the spindle by driving the spindle with the help of motor. The bearings provided in storage help smooth deployment and helps in minimizing the deployment load on booms and thus on motor.

4. Solar sail deployment unit

Easy integration of deployer and storage unit, and the modularity in the system were the major design objectives for the assembly of storage and deployer. From the learnings of the previous poorly designed deployment unit, due care was taken to avoid the difficulties during the integration, testing and sail attachment.

4.1 Coupling ring

Coupling the deployer and storage spindle provide advantage during the stowing of the sail and once the sail is completely deployed. In the deployed state, the locking provided to the motor shaft will directly lock the storage spindle preventing the possibility of rotation of spindle which may damage sail. But the spindles need to be decoupled for the testing iterations. This lead to the idea of using a coupling ring with D profile both on its outer and inner circumference. For coupling the spindles the ring is placed in the gap between the shafts of the spindles and removed whenever required.

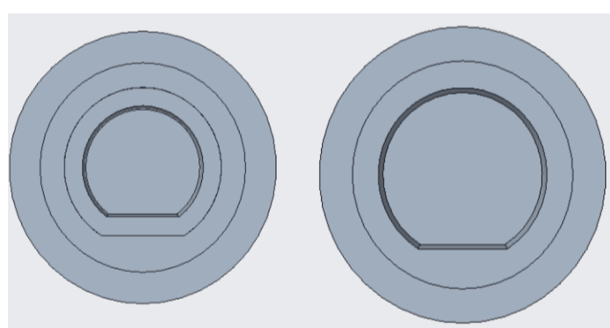
Fig. 15. With coupling ring (left) and without coupling ring (right)

4.2 Intermediate plates

The bolts of deployer has to be restricted from entering the storage volume. Also keeping modularity in consideration, intermediate plate is used. The holes and slots in the plate is made according to the bolts and nuts positions.

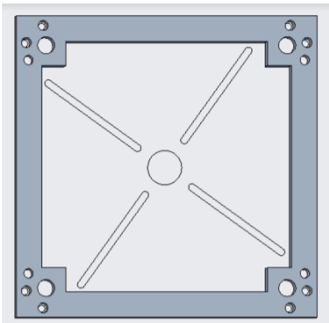

Fig. 16. Intermediate plate

5. Testing

The initial testing includes:

- Measuring the forces on boom due to sail during the deployment process. These values would be used for boom design.
- Measuring boom strength while deploying (changing boom length) for both bending (in plane, out of plane) and bucking failures.
- Testing the reliability of attachments used for connecting the sail to the central spindle.
- Testing the deployment with coupled spindles of the deployer and storage subassemblies.

. Testing the boom-sail deployment system without a set-up leads to several challenges like friction, effect of gravity and others which disturb the deployment process which in turn affect the results obtained. A set-up is required to eliminate these unideal conditions that hinder the actual deployment process.

5.1 Test setup

The solar sail system has to be qualified by ground testing. To qualify the sail with appropriate deployment, a proper set-up emulating actual conditions of deployment process and environment is essential. Different techniques has been used previously for eliminating the effects of friction and gravity on the results of testing.

5.1.1 Review of other setups

One of the ways emulating anti-gravity set-up is to hang the satellite (booms and sail) by strings from a frame fixed on the ceiling [6]. The above frame has rolling guides for the strings' upper end. There is a motor at the centre of the frame for copying the motion of the booms. This requires a base or table for supporting the sail. Booms cannot be tested for their strength using this set-up. For force testing, this set-up gives design value of the forces on the boom, since the guides enable ideal boom deployment without buckling.

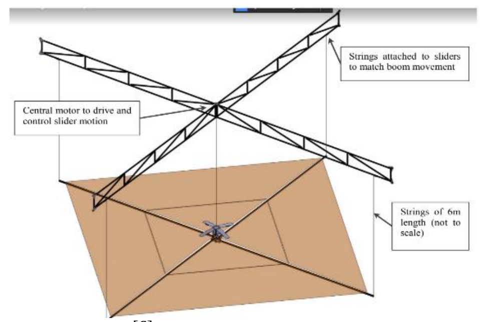

Fig. 17.[6] Deployment test set-up with gravity compensation

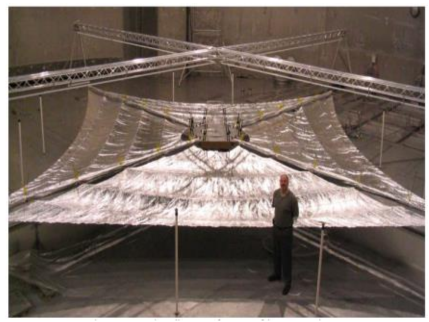

Fig. 18.[16] Solar sail system after vacuum deployment

Other method was to use helium baloons to support the weight of booms during deployment to create a 0g environment. As the mass of the booms increases during deployment, the helium baloon must have the flexibility of providing adjustable lift.

Fig. 19. [18] Boom deployment supported by a helium gravity compensation system

The third method which is used for test set-up of COEPSAT-2, is to use a deployment table for supporting the sail, smooth material like Teflon to reduce friction and guide rails to support the booms. The facilities and space available with the team for testing guided them to the third method.

5.1.2 Test set-up for COEPSAT-2

The design demanded to be suitable for all testing procedures and serve most of the conditions eliminating unideal nature thus enabling the creation of the closest actual scenario. Keeping in mind some of the basic requirements like support for the sail area and guides for the booms a table design was opted for.

The design involves a table for deployment having a cavity at centre for keeping satellite hub and guides for booms along the diagonals of the table. The quadrants are slightly raised in height as compared to the diagonals to fully support the sail area and thus provide the closest possible anti-gravity environment. The table comprises of triangular and rectangular frames which are joined together using nuts and bolts. Acrylic plates of corresponding appropriate shapes form the table top. Teflon is effectively used as a lubricant which reduces friction between the sail and the table surface. Acrylic sheets are positioned rigidly using fixtures that restrict its degrees of freedom in all directions. Fixtures are provided at the ends of beams to house the load cells and also to prevent torsion effect. The modularity of the table enables easy assembly and disassembly whenever desired. The frames can be divided into subassemblies and placed or removed from their position to approach the central hub for adjustments.

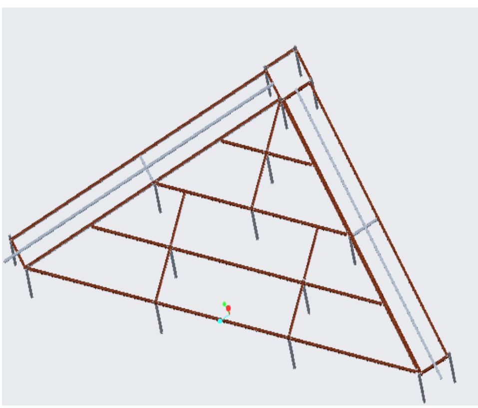

Fig. 20a. CAD model of Test bed frame

Fig. 20b. Test bed frame

Fig. 20c. Test bed with acrylic sheets

Fig. 20d. Central hub for satellite mounting

Conclusions

The solar sail deployment unit as discussed in the above literature, is a crucial part of the system for a solar sailing satellite. The mass, volume and power constraints of a pico/nano satellite add to the complexity of building a reliable deployment unit. Selection of boom profile and folding pattern shape the further development of the system. Design details usually overlooked at start may cause problems leading to delay in important testings, making appropriate provisions for the same will make the work easy. System validation is as important as the design and system building. Testing of mission critical mechanisms like sail deployment requires facilities for eliminating errors. Further, the test bed built would be used to test the deployment process, extract results required for design of booms, etc. The work presented here is a small part in the design of a 'Solar Sail System' which in addition to the present literature includes material testing, sail design for vibrations, analysis of wrinkling on thrust obtained and deployment dynamics. A through study of the above subjects and a continuous testing and analysis would result in a reliable 'Solar Sail System'.

References

[1] http://www.mylar.com/
[2] https://www.dupont.com/products/kapton-hn.html
[3] 'Design and development of a gossamer sail system for deorbiting in low earth orbit' – Juan M. Fernandez, Lourens Visagie, Mark Schenk, Olive R. Stohlman, Guglielmo S. Aglietti, Vaios J. Lappas, Sven Erb
[4] 'Fabrication and Development Testing of Solar Sail Quadrants for a 20-meter Solar Sail Ground Test System Demonstration' – Greg Laue, David Case and Jim Moore
[5] 'LightSail-1 Solar Sail Design and Qualification' – Chris Biddy and Tomas Svitek
[6] Martin Hillebrandt, Sebastian Meyer, Martin Zander and Christian Huhne, 'Deployment Testing of the De-Orbit Sail Flight Hardware'
[7] S J I Walker and G S Aglietti, 'A study of tape spring fold curvature for space deployable structures'
[8] K.A. Seffen, Z. You and S. Pellegrino, 'Folding and Deployment of Curved Tape Springs', Article in International Journal of Mechanical Sciences. October 2000
[9] Murphey, T.W. and Banik, J., "Triangular rollable and collapsible boom," March 1 2011, US Patent 7,895,795
[10] S. Guest and S. Pellegrino, "Analytical models for bistable cylindrical shells," in Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK, 2006.
[11] 'Modelling and Manufacturing of a Composite Bi-Stable Boom for Small Satelliites', FLORIAN HERLEM, STOCKHOLM, SWEDEN.
[12] 'Design and manufacturing of thin composite tape -springs', JAKOB EKELOW, STOCKHOLM, SWEDEN.
[13] 'Deployable Booms and Antenna Using Bi-Stable Tape-springs', Thomas Murphey, ARL.
[14] Adam Hoskin, 'Blossoming of Coiled Deployable Booms'
[15] Huang Xiaoqi, Liu Yufei, Zhang Xinghua, Cheng ZhengAi and Wang Li, 'Groung Testing of Solar Sail'
[16] David Lichodziejewski, Billy Derbes, Gordon Veal, 'Testing of a 10 m 4-Quadrant Solar Sail'
[17] Mr. Aditya Neralkar, Mr. Mihir Paranjape, Ms. Asawari Joshi, Mr. Rahul Patil, Mr. Abhijit Sharma, Mr. Akshay Deodhar, Mr. Sanjay Patil, Mr. Prathamesh Khare, Mr. Rohit Kulkarni, Mr. Kishan Patel, 'Analysis of Solar Sailing as a means of Orbit Maneuvering for nanosatellites in Low Earth Orbit'
[18] M. Leipold, M.Eiden, C.E. Garner, L. Herbeck, D. Kassing, T. Niedeerstadt, T. Kruger, G. Pagel, M. Rezazad, H. Rozemeijer, W. Seboldt, C. Schoppinger, C. Sickinger, W. Unckenbold, 'Solar Sail technology development and demonstration'