Deployable Parabolic Sail Structure for Solar Photon Thrusters

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A deployment solution for a parabolic sail structure for solar photon thrusters (SPTs) is presented. SPTs decouple the function of collection and reflection of light, achieving many advantages over flat solar sails. Although recent and increasingly realistic studies have concluded SPTs an unattractive option, the motivation behind this work is to progress the novel SPT concepts by resolving two problems identified: presenting a feasible solution for deployment and maintaining tight control over the collector shape; and addressing the space durability of carbon-fibre reinforced epoxy-resin composites for long duration solar sailing missions. Laterally curved bistable reeled composites were manufactured in such a way that their beneficial structural properties and bistable behaviour have been complimented with improved environmental resistance. This was achieved by implementing a cycloaliphatic based coating system reinforced with silicon nano-additive. The effect of curvature and additive on the natural frequency were investigated. In addition, response to vacuum outgassing, UV resistance, surface degradation due to atmospheric oxygen and thermal stability were investigated and improved.

Key words: deployable, solar sail, solar photon thruster, bistable reeled composites

1. Introduction

1.1. Background

The earliest recorded discussion of what we now call solar sailing dates back almost four hundred years to a letter between Kepler and Galileo. Several centuries later early in the 20th century, the concept reemerged and began to develop with the aid of engineering concepts.1,2 At this pioneering stage, the conditions under which solar sails could function were identified: additional propulsion is required in order to take the spacecraft outside the gravity field of a planet; the ratio of the radiation pressure to the mass density of the sail must be large; and the orientation of the sail to incident light and with respect to the desired trajectory is critical.

One of the greatest problems in exploiting large space structures is in their packaging and deployment given the volume constraints of past and current launch methods i.e. a rocket payload fairing. Early NASA feasibility studies into flat solar sails that could fit into the large but now-retired Space Shuttle bay investigated sail areas of $800 \times 800$ m$^2$.3 There have been recent successful in-space demonstrations of solar sails such as IKAROS4 and LightSail-15 (a 3U CubeSat). However, these space missions were only on the 15 m and 5 m scales respectively. Further progress has been hampered with the recent cancellation of the mission Sunjammer,6 previously under development to demonstrate a 38 m-span sail. Difficulties arose in manufacturing, a challenge of scalability that also affects laboratory testing7 when considering the vacuum facilities and gravity compensation required for such large areas of gossamer material.

The scalability of a design or piece of technology refers to its critical function’s invariance with respect to physical dimension. For the deployment of large solar sail concepts with extremely high length-to-diameter ratio booms, it is envisaged that truss structures be used.8,9 Examples include 350m-long trusses to deploy 500 m square sail for trajectories to the outer solar system - more examples can be found in a recent review.10

However well truss structures may perform for extremely large space structures, their mass efficiency is low for much smaller and lighter spacecraft such as CubeSats. Furthermore, it is difficult to fit a typical truss structure within the volume of a CubeSat. Conversely, storable tubular extendable members (STEMs),11 triangularrollable and collapsable mast (TRAC) booms12 and bistable reeled composites (BRCs)13 lend themselves to small satellite applications. The potential application of straight booms has been established and developments for deorbiting14,15 and solar arrays16,17 already exist.

1.2. Bistable Reeled Composites

BRCs are slit tubes which can be flattened and rolled up into a stable and compact coil (Fig. 1(a)). Past investigations on their bistable behaviour have focussed on straight BRCs.18-24 This behaviour enables BRCs to be stowed compactly using little to no constraint force and provide stable deployment - mitigating risk to the spacecraft that arises from uncontrolled deployment - using relatively simple deployment mechanisms.

Extending from established straight BRC literature, recent and ongoing research has developed the understanding of curved BRCs25,26 for which three main types are identified according to their Gaussian curvature: positive, negative and laterally curved (Figs. 1(b), 1(c) & 1(d)). The authors are motivated by the potential for exploitation of the latter, for the deployable parabolic sail structure of solar photon thrusters (SPTs).27

1.3. The Solar Photon Thruster (SPT)

SPTs decouple the functions of collection and reflection of light. As a consequence, many advantages over flat solar sails
(FSSs)\textsuperscript{29} are inherited including; maximising the effective collection area i.e. always Sun facing; higher thrust performance over all coning angles; low attitude control system requirements i.e. rotating a much smaller reflector positioned at the focal point of the SPT collector is easier than rotating an entire FSS; uniform temperature distribution of the sail surface; enabling larger payloads; reduced collector size due to higher performance; and possible combination of propulsion, power generation and high gain antenna functions.

Recent and increasingly realistic studies\textsuperscript{29,30} have concluded SPTs are an unattractive option, however, the motivation behind this work is to progress the SPT concept closer to the point whereby it becomes a viable option in solar sailing mission design. By addressing two problems identified; presenting a feasible solution for deployment and maintaining tight control over the collector shape and; ensuring operational longevity within the harsh space environment, progress in this direction has been made.

### 1.4. The Proposed SPT Collector Structure

The sail design envisaged is comprised of several laterally curved BRCs - a prototype is shown in Fig. 1(d). These can provide the out-of-plane deployment method and support structure for a suitably thin, lightweight and parabolic reflective material as illustrated in Fig. 2. This study focusses investigation and discussion on the curved slit tube support structure - the sail material and its packaging are not considered. However, the collector sail material should be continuously attached along the length of the curved tubes, such that tensioning ensures the smoothest possible reflective surface - this aspect of the SPT collector represents a great future challenge.

Laterally curved BRC prototypes were manufactured from carbon-fibre reinforced epoxy composite. Selecting CFRP material over metal reduces mass by approximately one third and enables manufacturing of bistable tubes which deploy in a more reliable way, consequently decreasing the chances of chaotic deployment.\textsuperscript{16} The SPT concept requires Sun facing at all times in order to produce reliable thrust, and the vibration characteristics of the support structure are investigated experimentally to conclude the reliability of the focal point. Using CFRP material comprised of an organic phase such as an epoxy resin matrix for applications requiring Sun exposures is not advised since most epoxy resins comprise of unsaturated chemical bonds (double and triple bonds) which are strong centres of UV absorption.\textsuperscript{31} Degradation of epoxy resins by UV radiation leads to mass loss by chain scissoring or crosslinking and embrittlement causing exposed structures to prematurely buckle, crack or erode which may lead to mission failure.\textsuperscript{32}
Additionally, for orbits of up to approximately 1000 km, space structures are not operating in a complete vacuum but rather within a residual atmosphere and are therefore exposed to reactive species, for which atomic oxygen is the most hazardous for organic materials such as epoxy resins.

Although solar sailing missions are envisaged to spend the majority of their mission life journeying through interplanetary space - and beyond - where atomic oxygen may not be prevalent, they may begin their operations and perform sail deployment from low-Earth orbit. Therefore, toughening CFRP against atomic oxygen is incredibly important for mitigating structural degradation at the beginning of mission life.

![Visualisation of the deployment of a solar photon thruster collector using four laterally curved BRCs in a 1U CubeSat](image)

To ensure reliable and extended operation of the sail structure, the space environment needs to be addressed and the material appropriately protected. In this work, a hybrid structure is presented that comprises of a core epoxy resin and a face epoxy resin with additional nano-reinforcement. The core resin is highly aromatic which ensures shape and stiffness due to the rigidity of the ring skeleton. The facing resin is used as a coating and is cycloaliphatic in the chemical character, which means its weather-stability and UV resistance are greater. The silicon nano-additive protects the surface from atomic oxygen bombardment and improves thermal stability of the coating. According to previous research, materials containing silicon erode two orders of magnitude slower than hydrocarbons due to the bonding character of silicon, the reactivity of oxygen towards silicon and formation of silica protective layer which acts as a self-passivation layer.

2. Method

2.1. Materials, Manufacturing & Vibration Testing

The material used to manufacture the core of the structure was a one part TGDDM resin system, MTM44-1 toughened epoxy resin (Cytec, USA) in an ultra-thin film form (Fig. 3(a)). This resin film was used to impregnate two plies of carbon-fibre braid (90 gsm, A&P Technology Inc., USA) and one unidirectional ply (32 gsm, Oxeon, Sweden) sandwiched in the middle. The material used for the protective coating was a cycloaliphatic epoxy resin (Huntsman, CY 184) cured with anhydride (Huntsman, Aradur 917 CH) in the presence of an accelerator (1-methylimidazole, DY070) as shown in Fig. 3(b). The nanophase reinforcement is an octa-functional polyhedral oligomeric silsesquioxane (EP0409 - Glycidyl POSS) supplied by Hybrid Plastics (Fig. 3(c)). POSS was added to the resin system in 5 wt% and the blend was sonicated in order to obtain good dispersion.

The protective coating was applied to the core laminate and the whole structure was cured from room temperature to 90°C with a ramp of 3°C per minute, dwelling for 45 minutes and then continue heating up to 180°C with the same ramp speed and dwelling for 2 hours. Such a curing cycle ensures proper curing of both the core epoxy and the outer epoxy surfaces.

Curved BRCs were manufactured using the same process, and vibration testing performed using a contactless laser method as demonstrated in previous work.

2.2. Characterisation for Environmental Compatibility

Material degradation is driven by the space environment. The four most influential conditions for carbon-fibre reinforced epoxy structure degradation are exposure to: high vacuum, radiation of short wavelengths e.g. UV, atomic oxygen and temperature extremes or cycling. In this work a comparable study between structures manufactured with and without a protective coating is presented.

Outgassing was measured after storing samples in vacuum environment (4 × 10^-5 mbar) for at least 24 hours. To observe effects of oxygen plasma etching, samples were exposed in an oxygen plasma afterglow created with a radio-frequency (13.56 MHz) power supply and an oxygen flow of 5 sccm. Thermal stability was evaluated with thermogravimetric analysis (TGA Q500, TA Instruments) in air, heating from room temperature to 850°C at 10°C per minute.
3. Results & Discussion

The results from vibration testing and characterising the environmental compatibility of samples manufactured (e.g. Fig. 4), are presented here with accompanying discussion. The natural frequency and environmental compatibility investigations presented are categorised as the BRC structural and material aspects respectively.

Laterally curved BRCs have been shown to exhibit bistability, confirming their potential exploitation for compact and lightweight deployable structures in small satellite applications. This work also shows that for various geometry of deployed tube e.g. straight, positively, negatively and laterally curved, it is the coil shape that appears to differ the most (Fig. 1). Straight BRCs produce cylindrical coils. Positively and negatively curved BRCs produce barrel and hyperboloid (e.g. hourglass-like) shaped coils respectively, whilst laterally curved BRCs produce half-hyperboloid coils (i.e. half hourglass). Unlike straight, positively and negatively curved BRC coils which are symmetric along their length, lateral BRC coils are not symmetric, with the coil radius of the two edges being different from one another. This aspect should be taken into account when designing appropriately shaped deployment mechanisms.

![Fig. 3. Chemical structure of the core and face cycloaliphatic resin](image)

(a) The core resin and amine hardeners

(b) Face resin cured with anhydride and accelerator

(c) Octa-functional POSS used as nano-modifier

![Fig. 3. Chemical structure of the core and face cycloaliphatic resin](image)

3.1. Structural: Natural Frequency & Focal Point

The natural frequency of cantilevered, straight BRC samples are presented in Table 1. For identical samples, additive (octa-functional POSS, Fig. 3(c)) appears to stiffen the BRC to produce a higher natural frequency. This result could be exploited and applied to all space missions using straight and curved BRCs in addition to primarily improving their environmental resistance.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Test 1, 2 &amp; 3 (Hz)</th>
<th>Avg. (Hz)</th>
<th>Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP</td>
<td>5.43, 4.82 &amp; 5.10</td>
<td>5.12</td>
<td>30.8</td>
</tr>
<tr>
<td>CFRP additive</td>
<td>6.65, 6.98 &amp; 6.59</td>
<td>6.74</td>
<td>31.2</td>
</tr>
</tbody>
</table>

![Fig. 4. A laterally curved BRC prototype. The deployed tube (top), different perspectives of the deployment (bottom-left and -centre) and the coiled up state (bottom-right)](image)

The natural frequency of cantilevered, laterally curved BRC samples are presented in Table 2. The natural frequency appears to be inversely proportional to lateral curvature. The consequences for collector design are that for a given focal point, its reliability becomes a greater issue for reflectors of small diameter due to the need for a highly curved BRC support structure which will exhibit lower natural frequency.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Test 1, 2 &amp; 3 (Hz)</th>
<th>Avg. (Hz)</th>
<th>Length (cm)</th>
<th>Radius of Curvature (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.06, 9.07 &amp; 9.09</td>
<td>9.07</td>
<td>45.9</td>
<td>46.7</td>
</tr>
<tr>
<td>2</td>
<td>7.84, 7.78 &amp; 7.81</td>
<td>7.81</td>
<td>48.2</td>
<td>29.2</td>
</tr>
</tbody>
</table>

The natural frequency of the sail support structure is of primary concern for ensuring a reliable focal point - good optics are critical for success of the SPT concept. A structure of low natural frequency is very susceptible to vibration and therefore every effort is made to produce BRCs with the highest possible
natural frequency. Other physical characteristics such as stiffness and dynamic stability are of secondary concern for a tensioned solar sail constantly facing the Sun, but can be improved as shown in recent work.\textsuperscript{26}

Appropriate integration of Samples 1 & 2 in Table 2 in a SPT collector would produce focal lengths of approximately 21.8 cm and 12.1 cm respectively given their curvature. Other curvatures are possible to manufacture in order to achieve the desired diameter of parabolic reflector and focal point. Sample 2 represents an extreme curvature of tube possible that crucially, still exhibits bistability - it is for this reason a sample of this type was manufactured and tested. Practically speaking, such highly curved BRCs would not be desirable for any real SPT collector due to their small diameter and tiny effective area. Sail diameters of up to 50–60 m using curved BRCs are envisaged (recall the Sunjammer mission would have used straight booms of approximately 27 m long to deploy a 38 m-span FSS).

3.2. Material: Response to Vacuum - Outgassing

Materials containing a volatile phase will lose mass in space due to outgassing. Especially moisture trapped in the polymeric matrix can be violently removed once the pressure drops. According to NASA outgassing recommendations,\textsuperscript{37} the total mass loss of a sample exposed in vacuum cannot be greater than 1%. The total mass loss measured during this study was 0.45% for an unprotected sample and 0.03% for a sample with a protective coating. This result shows that outgassing resistance is significantly improved with the coating application.

3.3. Material: Surface Degradation due to Atmospheric Oxygen

The presence of the surface coating is critical for prevention of erosion by atomic oxygen. The comparison between an unprotected and coated structure can be seen in Fig. 5. The full exposure parameters are presented in a previous study.\textsuperscript{38}

The addition of silicon to the epoxy resin matrix has a dramatic effect on the erosion yield of CFRP structures which is in agreement with previous studies.\textsuperscript{35} No signs of surface oxidation were observed on the coated surface whereas the uncoated structure suffered severe erosion.

3.4. Material: Thermal Stability

The spacecraft structure facing the Sun is operating in elevated temperatures up to 300°C. In order to evaluate the thermal stability of the curved BRCs proposed, TGA was performed on both the core resin and the facing resin systems, Fig. 6. The mass loss up to 150, 250 and 350°C is presented in Table 3.

One may notice the thermal stability of the face resin is lower than the core epoxy. This is due to the lack of aromatic rings that add to polymer’s thermal stability but have been removed from the surface due to their high absorption of UV radiation. However, both core and facing resin can be reliably used up to 300°C without significant mass loss and change in dimensional stability.

Glass transition temperature (T_g) is an important property of epoxy resins that indicates the transition from a brittle, glass-like material to a more flexible, rubbery one. According to the manufacturer both resins have high T_g of 190 and 200°C for

<table>
<thead>
<tr>
<th>Resin</th>
<th>Mass loss at 150°C</th>
<th>Mass loss at 250°C</th>
<th>Mass loss at 300°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face</td>
<td>2.86%</td>
<td>3.31%</td>
<td>6.09%</td>
</tr>
<tr>
<td>Core</td>
<td>1.39%</td>
<td>2.21%</td>
<td>4.81%</td>
</tr>
</tbody>
</table>
the core and the face resins, respectively. The hybrid face resin composed of cycloaliphatic/anhydride resin and reinforced with octa-POSS exhibits $T_g$ at 190°C (Fig. 7) which is lower than the neat resin. This is probably due to the fact that large molecules of octa-POSS increase the spaces between polymeric chains making them flow more easily.

Fig. 7. Glass transition temperature of the cycloaliphatic epoxy reinforced with 5 wt% octa-POSS

Samples were also exposed to prolonged high temperature in a vacuum oven at 250°C for 168 hours (one week). The mass loss recorded during this exposure is presented in Fig. 8. In the first 50 hours the sample exhibits rapid mass loss (approximately 17%), probably attributed to the effects of removal of unreacted parts of the polymeric chains and moisture. After this time, the mass loss rate is significantly lower at 4-5% over 118 hours until end of test. This low mass loss rate is encouraging for long duration solar sailing missions.

Fig. 8. Mass loss of the cycloaliphatic epoxy reinforced with 5 wt% octa-POSS during isothermal exposure in vacuum at 250°C

4. Conclusion

Laterally curved BRCs have been manufactured in such a way that their beneficial structural properties and bistable behaviour have been complimented with improved environmental resistance. It was shown that the natural frequency is inversely proportional to lateral curvature, impacting collector design. These BRCs are suitable for sail diameters up to and on the order of 50–60 m, lending themselves to the gap identified i.e. small satellite applications, due to their low mass, relatively simple deployment and recent in-space demonstrations. BRCs show inherently low torsional stiffness and a susceptibility to buckling which prevents their use for very large structures. However, tensioning of the sail material may aid in the buckling stability of very long curved BRC support structures. Truss structures appear better suited for extremely large solar sails that are 100s of metres across, however, progress is hampered with difficulties in manufacturing and testing due to the small size of current facilities on Earth. The manufacturing modifications presented result in BRCs with increased natural frequency and resistance to space environmental degradation by implementation of a cycloaliphatic based coating system reinforced with silicon nano additive. The saturated cycloaliphatic epoxy resists UV induced degradation and the addition of silicon prevents surface erosion by highly reactive atomic oxygen. TGA analysis showed that the maximum mass loss up to 300°C was about 6% and the structure shows a high glass transition at approximately 190-200°C which indicates a highly crosslinked resin system.

These results are encouraging for the suitability of laterally curved BRCs manufactured with improved environmental compatibility for use in long duration solar sailing missions.

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References