An application of Tape Springs in Small Satellite Area Deployment Devices

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Abstract

In recent years there have been many advances in the miniaturization of electronic and mechanical technologies for space applications. However, the satellite power requirement does not reduce linearly with the satellite mass, creating the need for small satellite deployable arrays. This paper outlines the current state of technology for small satellite deployable structures, briefly discussing the current and near future systems that have been made known to the international scientific community. A concept design outline of a nano satellite area deployment device is then presented. This design makes use of tape springs to drive the deployment of a solar array blanket in three dimensions. Further research in this area is then briefly outlined.

Introduction

Over the last fifteen years there has been growing research and advances in the miniaturization of electronic and mechanical technologies (for example, micro sun sensors, micro-gyroscopes etc [1]). It now possible to construct satellites weighing only a few kilograms, thereby dramatically reducing the cost of access to space. Such development opens up many new possibilities for space exploration at low cost for a far wider community of scientists and businesses. In-fact, many nations have identified nano-technology as a critical technology underpinning advances across many market sectors. However, as the total satellite mass reduces, the power requirement of the satellite, in many applications, does not reduce at the same rate. For example, the small size of cellular telephones and hand held receivers for the Global Positioning Satellite (GPS) navigation system creates a need for larger antenna sizes in the space-based components of the system. Greater capacity requires greater on-board power, provided by deployed solar arrays. There is also ongoing research into the use of ion propulsion systems, as primary and secondary propulsion for small satellites, due to their low mass potential. Such systems would also significantly increase the power requirement of the satellite. Usually micro and nano satellites employ body mounted solar cells, however, there is growing interest in deploying photovoltaic cell areas larger than the surface area of the bus face. Small, cheap, reliable and efficient deployment methods are therefore required to meet the potential of future small satellite missions.

This paper focuses on the supporting deployable structure for not only current and future array blankets, but any space application that requires an area deployment device (for example: solar sails, de-orbiting devices).

Current Technology

Over recent years many small satellites have been launched. The vast majority of these satellites have been technology demonstrators, and have had body mounted photovoltaic cells. The small satellites that currently require higher power levels use simple, single hinge fold out panels.

As the future power requirements of these small satellites is likely to rise, companies specializing in this field have begun researching low mass, area deployment devices. Such companies include AEC-Able, AeroAstro, The Aerospace Corporation, L'Garde and the Deployable Structures Lab. It should be noted at this stage that there may be many more concepts under development for which (due to military or commercial reasons) information has not been publicly released. Some companies have identified inflatable structures as the key technology for small satellite deployable structure. Other companies have used traditional technologies in novel designs. Four example designs include the Deployable Structures Lab (DSL) design study for QinetiQ (UK) (developed for micro satellites [2]), AEC-Able's Ultraflex Array (developed for micro satellites [3]), L'Garde's inflatable ITSAT array (developed for micro satellites [4]) and Aerospace Corporation's Powersphere (developed for micro/nano satellites [5]).

The first three systems listed are aimed at micro satellites (i.e. satellites with a mass of around 50 - 100kg) and they each demonstrate different design philosophies. These systems all deploy perpendicular from the bus face. The Powersphere concept is aimed at very small satellites weighing from under one kilogram to 60 kilograms. (This study focuses on very low mass systems, such as the powersphere, and as this is the only real nano satellite design, it is the only system which is discussed further.)

Developed by The Aerospace Corporation, the PowerSphere Nanosatellite has received the patent for the deployable geodesic solar-panel array consisting of connecting pentagon- and hexagon-shaped panels that are solar-energy-collecting cells. Folded in a flat stack at either end of a strut attached to the payload, the panels of two halves of the PowerSphere unfurl during deployment, creating two hemispheres that interlock and encase the satellite. Once deployed the PowerSphere becomes a 360-degree solar array that collects a constant amount of electric power regardless of its attitude relative to the sun. Encasing the satellite is a design feature which would be an advantage for some missions as it provides a controlled thermal environment for the nanosatellite electronics and battery [5]. However, for missions which rely on scientific sensors and cameras, encasing the satellite would not be a feasible solution to supply the required power.

Design Layout

This research study aims at designing and producing an area deployment device for low-mass satellites (10 - 15 kg). Key design drivers for low-mass satellites are reliability and low cost. This dictates that an area deployment system needs to be as simple as possible to reduce the risk of deployment failure. Expensive systems would significantly increase the total mission cost and would reduce the financial appeal of such small satellite missions. The extreme low-mass requirement dictates that the photovoltaic cells must be supported on a blanket array. Researching the methods of structurally supporting blanket arrays, it was concluded that a 'simply supported' array would be the most suitable design. Simply supported, in this context, means that the array is supported at each of the corners by structural members running along the diagonals of the array (See figure 4a). The widely used example of this is a kite. For this design the optimum array geometry would be a square. To achieve the maximum density of photovoltaic cells on the blanket, (i.e. to maximize the power density of the array) the array must have the minimum achievable number of fold lines. Conversely, the area between the fold lines must be the maximum possible. The maximum possible area, between fold lines, (for a compactly folded array) is the area of the bus Sun face. The largest simple deployable area of array would therefore be nine times the area of the bus face. This can be seen in figure 1. This has implications on other satellite systems, for example the positioning of sun sensors, however this is beyond the scope of the present work. The baseline structure for the array has been chosen to be tape springs, due to the fact that they require no moving parts, lubrication or locking devices and once deployed have good structural properties. This structure can be optimised for different size arrays to ensure that the array meets the stiffness requirements of the specific mission. To reduce the structural mass to a minimum the array would be mounted centrally to the sun facing edge, reducing the cantilever length of the structure.

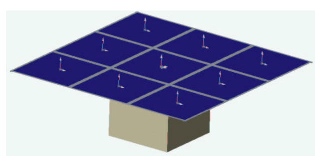

Figure 1: Nine panel array

This area deployment configuration has been studied at DSL for a de-orbit application (also using a tape spring structure, see reference [6]) and has also been used as a solar sail, developed by L'Garde (with inflatable ribs), for the Team Encounter mission.

Structural Folding

This array, with this arrangement of fold lines, would deploy in two stages as shown in figure 2. With structurally supporting tape springs running across the diagonals of the array (see figure 4a), it can be seen that this deployment would require three dimensional folding, and deployment of the tape spring structure. Figure 3 shows a finite element model of a three dimensional tape spring fold. The tape at the corner of the bus face, however, needs to be folded about one axis to fold the open array into the stage 2 position, then about another axis to fold the array into the stage 1 position. To make this design physically achievable, either the bus dimensions, the

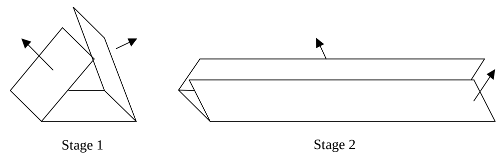

Figure 2: Deployment Stages

array dimensions or the location of the folds needs to be altered. An example of this is shown in figure 4.

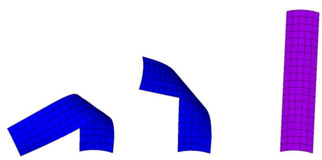

Figure 3: Finite Element model of a 3D fold in a tape spring

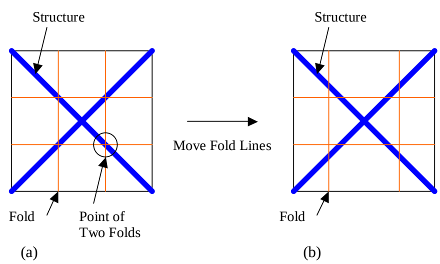

Figure 4: Alteration of the fold location

The deployment of tape springs has been studied by Cambridge University, and the Deployable Structures Lab in Cambridge, UK [7]. However, this research has focused on the deployment dynamics of tape springs in two dimensions. Therefore, before the deployment of this array could be modelled, the deployment dynamics of tape springs in three dimensions needs to be determined. Before this can be achieved it is important to understand the folding dynamics of tape springs.

Analysis Background

Tape springs are defined as thin metallic strips with a curved cross section, which has the key property that it is continuous (i.e. contains no mechanical hinges or other folding devices) and yet it can still be folded elastically. In standard, two dimensional, tape spring analysis, the springs are loaded by a pair of equal and opposite bending moments, M, which cause them to bend in the 'soft' plane of bending as shown in figure 5 (where R_L, R_T are the longitudinal and transverse radii of curvature of the tape spring). The general sign convention is that a positive bending moment induces tensile stresses along the edges [8]. The bending induced by this positive moment

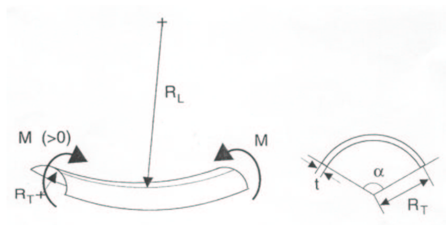

Figure 5: Tape spring subject to M>0, and its cross-section

is known as opposite-sense bending because it produces a change of transverse curvature that is of opposite sense to the initial transverse curvature of the of the tape spring. Conversely, a negative bending moment induces compressive stresses along the edges of the spring, and is referred to as equal-sense bending. The corresponding longitudinal rotation of the tape spring, θ, (which is positive, for a positive applied moment) is the key deformation parameter in this study.

For two dimensional analysis the moment, rotation relationship is shown in figure 6 (where M_+^{max}, M_-^{max} are the peak moments for opposite-sense and equal-sense bending and M_+^*, M_-^* are the steady-state moments for opposite-sense and equal-sense bending.) It can be seen that the tape spring snap through at A and F.

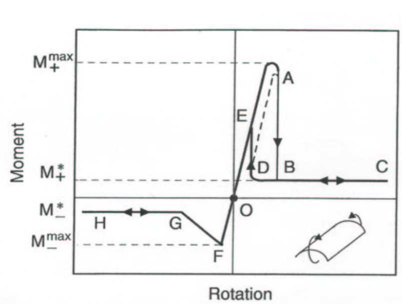

Figure 6: Graph of Moment-Rotation relationship for a straight tape spring

This relationship is modelled theoretically by Mansfield, [9], however, simple models for M_+^* and M_-^*, shown below, can be obtained through simple shell theory [10].

$$M_+^* = (1+\nu)D\alpha \tag{1}$$

$$M_{-}^{*} = -(1-\nu)D\alpha \tag{2}$$

Where:

ν Poisson's ratio

D flexural rigidity

α angle subtended by cross-section of spring

θ relative rotation of elastic folds

Tape Spring Deployment in 3D

A critical parameter for the deployment of the array in three dimensions, is the steady state moment M* and how this value changes throughout the deployment. The theory currently available needs to be extended and validated through experimental testing, which will investigate M* in three dimensional deployment. The system has been modelled using finite element analysis, to compare this analysis approach to the experimental results. Along with the steady state moment M*, the twisting moment of the tape will also be determined experimentally. The combination of the twisting moment, and the longitudinal steady state moment M* defines the nature of the deployment. Ultimately, an accurate model of the 3D deployment sequence is required. This type of deployment will be further investigated using experimental testing, finite element analysis and shell theory. Such theories would contribute to the current knowledge of two dimensional deployment as torsion and bending are coupled in the buckling of tape springs subject to negative (i.e. equal sense) bending moments.

Conclusions

In this paper the current state of technology for micro and nano satellite deployable structures has been briefly outlined, discussing the current and near future systems that have been made known to the international scientific community. A conceptual design for a small satellite deployable array has also been presented. This outline design uses tape springs folded in three dimensions to drive the deployment. Such a design could be scaled up, with a corresponding increase in structural strength, to produce a family of very adaptable deployment designs. The necessity for accurate three-dimensional tape spring theories is emphasized to accurately model the deployment.

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