International Journal of Solids and Structures 118–119 (2017) 58–69

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Tip force during blossoming of coiled deployable booms

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ARTICLE INFO

Article history:
Received 29 July 2016
Revised 19 February 2017
Available online 18 April 2017

Keywords:
Deployable booms
Tape springs
Solar sailing
Drag deorbiting
Blossoming

ABSTRACT

Deployable booms are an essential part of the deployable structures family used in space. They can be stowed in a coiled form and extended into a rod like structure in an action similar to that of a carpenter's tape measure. "Blossoming" is a failure mode that some boom deployers experience where the booms uncoil within the deployer instead of extending. This paper develops a method to predict the force that a boom can exert before blossoming occurs by using the strain energy stored in the coiled boom and in the compression springs. An experimental apparatus is used to gain practical results to compare to the theory.

1. Introduction

Deployable structures have been essential for space applications due to the limited volume available in launch vehicles and the requirements of large elements once in space such as: solar panels, solar sails and antennae. Coiled deployable booms developed from an invention by George Klein, working at the National Research Council of Canada. The original application was a radio beacon that would be dropped by military aircraft and deploy an aerial once on the ground (Bourgeois-Doyle, 2004). This initial design developed into the Storable Tubular Extendible Member (STEM) manufactured by the De Havilland Aircraft company of Canada for use as antennae on Canada's Alouette 1 satellite (Mar and Garrett, 1969). Further work was carried out by Rimrott to characterise the properties of STEM booms, including the bending stiffness, the torsional stiffness, and the boom self deployment speed (Rimrott, 1966; Elliott and Rimrott, 1966; Rimrott, 1967). While the cross section of STEM booms usually subtended angles of at least 360°, making them tubular in shape, booms with smaller subtended angles were also developed for other purposes, such as deployable membrane reflectors (Seffen et al., 2000b) or as hinges for deployable panels (Seffen et al., 2000a; Walker and Aglietti, 2007). These booms with smaller subtended angles were termed tape springs. For these applications a deeper understanding of the moment - bend angle relationship was needed to model the deployment dynamics of the booms so the behaviour of the panel and reflector could be predicted (Seffen, 1997). The use of glass fibre and carbon fibre composites in booms enabled a further development. An invention by Andrew Daton-Lovett used composite materials to create booms that exhibited bistability, enabling a boom that was stable in its deployed state but also in its coiled state (Iqbal and Pellegrino, 2000; Guest and Pellegrino, 2006; Fernandez et al., 2014; Galletly and Guest, 2004a; 2004b). This allowed booms to be coiled and stored without any constraints, which is useful in a number of applications. Bistability can also be created in booms made of isotropic material by prestressing the boom during manufacture (Kebadze et al., 2004). Different cross section booms have also been developed for different applications such as the lenticular DLR boom (Sickinger and Herbeck, 2002; Herbeck et al., 2001), and the Triangular Rollable And Collapsible (TRAC) boom (Banik and Murphey, 2010). More recently there has been a growing interest in the use of coiled deployable booms for solar sailing missions such as NanoSail-D2 (Johnson et al., 2011), LightSail (Biddy and Svitek, 2012), DeorbitSail (Stohlman et al., 2013) and InflateSail (Viquerat et al., 2015). At the Surrey Space Centre the CubeSail solar sailing mission (Lappas et al., 2011) uses four coiled deployable booms to deploy four triangular sails. During deployment testing a problem occurred when the booms would uncoil inside the deployer instead of deploying the sails. This issue was termed "blossoming" and had been encountered in missions with similar deployer designs (Biddy and Svitek, 2012; Stohlman et al., 2013; Fernandez et al., 2013). Section 2 describes the blossoming problem in more detail. Section 3 describes a method using the strain energy in the coiled boom and compression springs to estimate the tip force during blossoming. This method has been developed using tape spring booms with a subtended angle of less than 180° for simplicity and as a proof of concept. Further work would be needed to extend this method to other boom types and to capture possible effects that other boom cross sections might

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http://dx.doi.org/10.1016/j.ijsolstr.2017.04.023

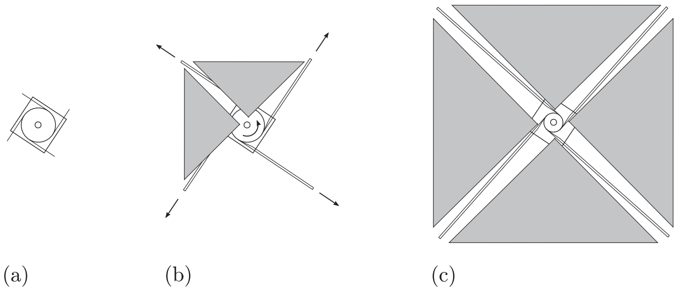

Fig. 1. The deployment sequence of CubeSail. (a) The four booms are co-coiled around the central spindle inside the deployer. The folded sails sit on top of the deployer (omitted for clarity). (b) CubeSail part way through deployment; the central spindle turns, the booms extend and deploy the sails (two sails are omitted). (c) The fully deployed booms and sails.

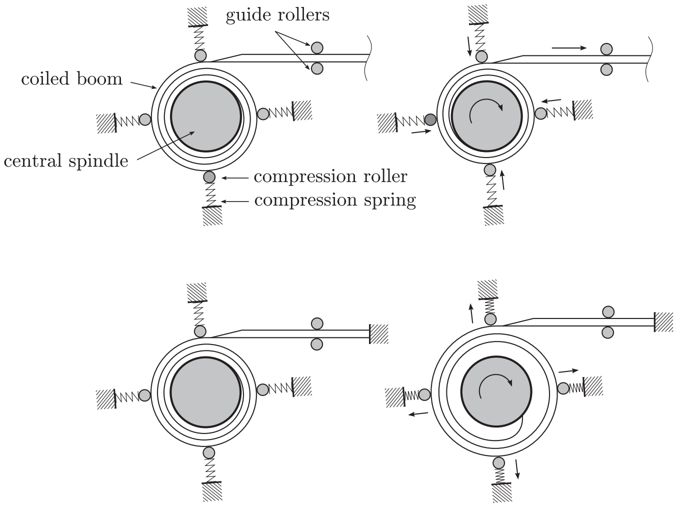

Fig. 2. The top two diagrams show the normal deployment of a coiled boom. The coil and central spindle turn at the same rotational speed. On the outside of the coil the boom changes into its deployed state and is guided through the guide rollers and out of the deployer. As the boom coil decreases in diameter the compression rollers move towards the centre of the spindle, keeping a force on the outside of the coil. The bottom two diagrams show blossoming. The sail tension has become too great for the deployer causing the tip of the boom to stop moving. In this instance the central spindle turns but the rotation of the outside of the coil slows or stops, instead the coil grows inside the deployer.

exhibit. Section 4 explains how the experimental apparatus works. Section 5 compares the practical results to the theory described in Section 3, and Sections 6 and 7 discuss the results and conclude the paper.

2. Blossoming

This section describes the blossoming problem that can occur when using deployable booms. The most common example of a deployable boom is a carpenter's tape measure. In its unstrained, deployed state a tape measure has a curved cross section which increases its stiffness, helping it maintain its shape when in a cantilevered load state. When coiled around a spindle, the cross section becomes flat and the tape becomes curved in the longitudinal direction. Some deployable booms are stored in a deployer; this is a mechanism that constrains the boom until it is ready to be used, then aids the deployment process. CubeSail (Lappas et al., 2011) has four booms that deploy four triangular sails to form a square solar sail as shown in Fig. 1. The CubeSail deployer and other similar deployers have booms that are co-coiled around a single central spindle as shown in Fig. 3. The four booms are attached to the central spindle at 90° to one another, they form a coil and exit the deployer at 90° intervals. Compression rollers stop the coil from expanding and guide rollers guide the booms out of the deployer. Fig. 2 shows a simplified version of a deployer with a single boom. During normal operation a motor turns the central spindle and the coiled boom is deployed. The part of the boom on the outside of the coil leaves the deployer and changes to its unstressed state with a curved cross section. As the boom coil shrinks in size, the compression springs extend. This maintains the force applied by the compression rollers to the outside of the coil to prevent it expanding.

During deployment testing it was found that blossoming would occur. This is when the central spindle turns but the coiled boom stops deploying and instead unwinds within the deployer, as shown in Fig. 2. A similar motion happens with the four co-coiled booms as seen in Fig. 3. This causes the mechanism to jam and can damage the booms.

During the early stages of the CubeSail testing program the deployer worked satisfactorily without the sails attached. When the sails were added, and the booms and sails were deployed, blossoming started to occur. Fig. 4 shows the torques and forces within the deployer. The solid arrows represent the forces and torques applied by the boom, and the dotted arrows are the forces and torques applied to the boom. An unconstrained coiled boom will tend to uncoil and requires torques applied at either end to prevent this. As the coil changes from a coiled state to a deployed state it has a reduction in strain energy, this leads to a self deployment torque (Tsd) in the transition region on the outside of the coil. The guide roller opposes this torque with a force at a distance from the coil. The other end of the coil is attached to the central spindle. The coiled boom would change to a lower energy state if the central spindle turned clockwise, this leads to a central spindle torque (Tcs). In the CubeSail deployer there is a motor that controls the rotation of the central spindle, this motor opposes the central spindle torque. When there is no tip force the self deployment torque and the central spindle torque are equal and opposite to one another. During deployment the boom extends and uncoils the sails. As the sails are uncoiled and unfolded they will offer some resistance to the boom's extension. This is shown as sail tension in Fig. 4. The boom tip force arises from overcoming the sail tension and is equal and opposite to it. The deployer can produce a certain tip force but if the sail tension is too great the deployer will blossom. This paper describes a model that predicts how much tip force a deployer can provide before it blossoms. There are three contributions to the force that a boom can provide before blossoming: the energy minimum within the coiled boom, the compression spring energy, and the friction between the layers of the boom. The friction within the coil is not examined in this paper but its effect can be seen in the results as an increase in the tip force as the compression roller force was increased.

3. Energy method

Work carried out on the self-deployment of STEM booms (Rimrott, 1965; 1967; 1980; Upadhyaya, 1968) resulted in the development of a method that used the strain energy stored in the coiled boom to predict the force that drove the extension. By using the force and taking into account the inertia of the boom, the deployment speed and time could be calculated. The following model uses a similar energy method but links the change in coil radius to the change in length of the boom within the deployer as blossoming occurs.

When a tape spring boom is coiled and the angle subtended by the coil is fixed, it will try and form a circle that has the same radius as its natural cross section due to its energy minimum in that state (Calladine, 1988; Hoskin and Viquerat, 2016). A further force is needed to hold the coiled boom at a radius other than its