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Nonlinear dynamics of thin-walled elastic structures for applications in space

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ABSTRACT

Driven by the need for multi-functionality and increasing demands for low mass and compact-stowing, unfolding, self-deploying or –morphing smart mechanical structures have become popular space engineering designs for flexible appendages. Extensive research has been conducted on the use of tape springs as hinge deployment mechanisms for space booms, solar sails, or optical membranes or directly for used as antennas. However, the vibrational behaviour of tape springs and its related dynamics have rarely been addressed in detail, even though missions are underway with similarly flexible appendages installed.

By conducting quasi-static bending tests on a tape spring antenna, we evidence hysteresis behaviours in both the opposite- and equal sense bending directions. Apart from the well-known snap-through buckling, the structure exhibits torsional buckling in the equal sense bending direction before collapsing. Micro-vibrational excitation triggers nonlinear jump phenomena and the period-doubling route to chaos. Using a computational tape spring model and simplified environmental loads similar to those encountered in near-Earth orbits, coupling between the first bending and torsional modes generates a dynamic instability which is predicted by a complex eigenvalue analysis step. The current study highlights that high perturbation sensitivity and system-inherent nonlinearities can lead to stability issues.

In the course of designing a spacecraft with thin-walled appendages, system-level trade-offs are routinely performed. Since it is unclear how severely the vibrations of flexible appendages might affect their proper functioning or the control of the spacecraft, it is of paramount importance to validate experimentally thin-walled structures thoroughly for their dynamic and stability behaviours.

1. Introduction

Compact, light-weight nano- or pico-satellites such as cubesats have become popular alternatives to conventional satellite designs with production and launch costs often being reduced to only a few hundred thousand US$ [1–3]. However, higher performance in the form of larger antennas, optical mirrors and reflectors, or solar sails and panels, and scientific advancement, strongly push for the development of miniaturised, efficient and highly packed, area deployment devices

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[4–7]. Consequently, the thickness of thin-walled structures must be further reduced for enhanced stowage or reduced weight [4–9]. It is known, however, that high *imperfection sensitivity* fosters buckling instabilities [4,7,9,10]; further, that thin-walled, slender structures often show significant *geometric instabilities* and therefore suffer from large deflections even with miniscule loads applied. While operating, especially at altitudes up to 800 km, in low Earth orbit, a spacecraft is exposed to both, external and internal perturbations. External perturbations include changing environmental loads such as caused by solar radiation pressure, large temperature differentials, electromagnetic and gravitational fields and residual atmosphere; internal perturbations include micro-vibrations as caused by thrusters, electric motors or the attitude control system such as a reaction wheel assembly or magnetorquers [11,12]. As a consequence, large amplitude nonlinear vibrations of thin elastic shells [13] can lead to undesired dynamics and possibly a performance reduction, which may trigger unforeseen satellite behaviour, even putting a mission at risk [14–18].

Owing to their structural simplicity, self-deploying and self-locking characteristics, thin-walled structures - especially open cylinder segments such as spring tape measures – have attracted much attention in recent years [4–7,9,18–26]. Yang et al. [20] tested single layer and double layer tape spring hinge designs and highlighted the good quasi-static deployment performance with regards to structural stress, and the peak and steady moment development. Kim and Park [21] studied solar array hinges and were concerned with the overshoot behaviour during deployment. Jeong et al. [22,23] developed a new shape memory alloy dampers for solar array hinges with higher bending stiffness and shock spectrum characteristics to accommodate the launch dynamics. Jennings et al. [24] studied the kinematics during deployment and pointed out an overshoot of about 60° of the boom before the steady state dynamic behaviour is reached, which was related to the character of the tape spring hinges.

Recently, Dewalque et al. [25] studied using numerical analyses and experiment, via motion analysis and a synchronised force plate, the nonlinear behaviour of tape spring measures to be used as a deployment mechanism. Results show that the deployment can be divided into three phases, which are characterised by different types of folds, oscillation frequencies and damping behaviours [25]. Damping is essential in determining the correct deployment dynamics of tape spring booms [13]; however, with increasing deployment length tape springs show decreasingly lower damping values accompanied by an increasing modal density, rendering their vibrations difficult to control [4]. Piergentelli et al. [26], Reveles et al. [27], and Fernandez et al. [28] employed tape spring structures as lightweight antennas or space booms; however, only launch qualification is reported with no detailed dynamic vibration analysis being conducted – even though their structures are rather thin-walled and slender and susceptible to complex vibrations [13,28].

Hoffeit et al. [18], Guinot et al. [29], Soykasap [6,30] and Soykasap et al. [31], Walker [7,32], Seffen and Pellegrino [9] or Seffen et al. [33] studied the mechanical properties of tape springs including their moment-rotation, static stability, profiles or temperature dependency. Tape springs are rigid owing to their longitudinal or transverse (cross-sectional) curvatures [4,9,33]. Bending a tape spring in the ‘opposite sense’ requires more force than applying load to the ‘equal sense’ bending direction [4,5,7,9,18,29]. When the moment rotation relationship of a clamped tape spring is measured, it shows a strong hysteretic behaviour in the opposite bending sense; contrary to that, the equal sense bent structure indicates a linearly increasing then decreasing moment until a steady-state moment is reached [6,7,9,18,20,29,34]. Three-dimensional folds result as a combination of twisting and bending, and develop quickly if asymmetries are present (e.g. in the mounting angle of a skewed spring tape’s hinge) [7,29]. Folds generated by ‘equal sense’ bending may have two co-existing asymmetric equilibrium points and bi-stability combined. This may occur at relatively small rotation angles when sensitivity to imperfection causes improper deployment of a tape spring [24,31–33].

However, while the opposite sense bending direction has been well studied [6–9,29–33], a discussion about the hysteresis behaviour in the equal sense bending direction of tape springs is not as well documented to the best of the authors’ knowledge. An experimental, ground-based validation of thin-walled slender structures remains difficult [4]; modelling and analysis require consideration of local material and global, geometric nonlinearities [8,28,29]. Further, despite their popularity as design elements nowadays [4–7,9,18,20,24,29,31–34], the dynamics of tape springs due to vibrations has not been studied in detail yet.

Hence, starting with static bending tests, we extract hysteresis curves for both the equal and opposite sense bending direction of clamped-free, single layer, tape spring configurations and the buckling instability margins (BIM) are determined. To study the effects of internal vibrations as caused e.g. by the periodic excitation of a reaction wheel assembly, the vibration response dynamics of a periodically excited thin-walled structure is studied. To evaluate the risk of self-excitation, a complex eigenvalue analysis is finally conducted using a numerical model of an experimentally updated tape spring [4].

2. Buckling instability margins

2.1. Experimental setup

The geometric parameters of the tape spring (Stanley 30-497, total length 5000 ± 0.2 mm, width 19.1 ± 0.2 mm) are depicted schematically in Fig. 1(a). We obtained the characteristic curvature, the elastica, by bending the tape spring in the opposite sense direction and holding it together at both ends [7,19]. A secondary curvature along its longitudinal axis in the opposite bending direction (Fig. 1(a)), similar to curved tape springs, led to a slight deflection of 8 mm at 1300 mm deployment length which is assumed to follow a parabola [4,5,9,33]. We used a clamped-free configuration to