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Experimental validation of tape springs to be used as thin-walled space structures

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A B S T R A C T

With the advent of standardised launch geometries and off-the-shelf payloads, space programs utilising nano-satellite platforms are growing worldwide. Thin-walled, flexible and self-deployable structures are commonly used for antennae, instrument booms or solar panels owing to their lightweight, ideal packaging characteristics and near zero energy consumption. However their behaviour in space, in particular in Low Earth Orbits with continually changing environmental conditions, raises many questions. Accurate numerical models, which are often not available due to the difficulty of experimental testing under 1g-conditions, are needed to answer these questions.

In this study, we present on-earth experimental validations, as a starting point to study the response of a tape spring as a representative of thin-walled flexible structures under static and vibrational loading. Material parameters of tape springs in a singly (straight, open cylinder) and a doubly curved design, are compared to each other by combining finite element calculations, with experimental laser vibrometry within a single and multi-stage model updating approach. While the determination of the Young's modulus is unproblematic, the damping is found to be inversely proportional to deployment length. With updated material properties the buckling instability margin is calculated using different slenderness ratios. Results indicate a high sensitivity of thin-walled structures to miniscule perturbations, which makes proper experimental testing a key requirement for stability prediction on thin-elastic space structures. The doubly curved tape spring provides closer agreement with experimental results than a straight tape spring design.

1. Introduction

Flexible, deployable thin-walled structures, lightweight and low cost, with highly compact packaging, self-deploying and even self-locking capabilities, have become increasingly popular designs in space engineering. Examples include tape spring hinges, thin-elastic umbrella designs and other foldable structures including bascule bridges or origami constructions [1, 2]. In particular, thin-walled open cylinders in the form of tape springs have attracted much attention [5–9]. However, due to material inhomogeneity, geometrical nonlinearities and their sensitivity to imperfections, thin-walled structures show different types of nonlinear behaviour [3, 4].

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Nomenclature

$\mathbf{C}$	Damping matrix
E	Young's modulus
$\mathbf{K}$	Stiffness matrix
l	Tape spring length
m	Tape spring mass
$\mathbf{M}$	Mass matrix
n, N	Number of samples
r_c	Characteristic radius (elastica)
S	Circumference/arc length of open cylinder (to calculate α)
p	p-value (calculated probability)
t	Thickness
w	Tape spring width
y	Deflection due to *secondary* curvature
α	Mass proportional damping factor
β	Stiffness proportional damping factor
γ	Half subtended angle
δ	Density
λ	Slenderness ratio = tape spring length divided by its radius of gyration
μ	Mean value (central tendency of data)
ν	Poisson's ratio
ω	Eigenfrequency
ρ	Pearson correlation coefficient
σ	Standard deviation (scattering of data)
ξ	Damping ratio
B&K	Bruel & Kjær
BIM	Buckling Instability Margins
CI	Confidence Interval (95%)
FRF	Force Response Function
MAC	Modal Assurance Criterion
SR6	Eight-node shell element (ABAQUS)

Mansfield [10] studied analytical expressions of large-displacement relations of curved lenticular and constant thickness strips, exhibiting torsional and snap-through (nonlinear) buckling [10]. For large tape spring structures, the torsional motion becomes more prominent; however, even analytical models, which are accurately able to reproduce three-dimensional folding behaviours, are yet to be developed [4, 6, 7]. Seffen and Pellegrino [11] studied the dynamics of tape spring deployment actuators and classified between (i) equal- and (ii) opposite-sense bending (moments) of tape springs which act around the transverse direction, deflect the structure and cause buckling. Equal or opposite sense bends produce a longitudinal radius of curvature either on the same or the opposing side to the initial transverse radius of curvature relative to the moment loads and produce localized folds [12]. Equal-sense bending is characterised by two line contacts at the edges of the tape spring; it introduces longitudinal and transverse curvatures and a more gradual fold development via torsional buckling. The opposite bending produces a centred line contact [13,14]. The bi-stability of two co-existing, asymmetric equilibrium points can cause improper deployment dynamics, for small rotation angles and very small gravitational effects, material and loading imperfections [5]. Walker and Aglietti [6, 7] reported three-dimensional folds of combined twisting and bending as a result of asymmetric loads.

The material properties play an important role in space engineering. Composites and various kinds of steel with largely varying elastic properties (e.g. Young's moduli of from 131 MPA to 630 GPa) are used [6,7,11,14]. Reveles et al. [15] designed a deployable and retractable composite space payload or antenna boom shaped as thin-walled, open cylinder, with large curvature and 0.3 mm thickness for improved stability. Piergentili et al. [16] used a carpenter's tape spring measure as a satellite antenna while Fernandez et al. [17] studied an ultra-lightweight deployable composite boom's unfolding kinematics to span a solar membrane which can also be employed as a deorbiting device. Otherwise, combinations of tape spring hinges e.g. a double-layered tape spring or combinations of equal sense and opposite sense bent tape springs, are used, and provide higher rigidity and improved self-deployment or self-locking [3, 18–21]. Soykasap [22] designed a deployable and integrated three-tape spring hinge. For temperatures greater than 50 °C the dynamics of the spring hinge changed significantly: its eigenfrequencies decreased while its vibration attenuation time grew. However, the dynamics of tape springs due to changed material or thermal properties is rarely studied experimentally (e.g. Ref. [23]), and higher frequencies are generally neglected.