CHARACTERISING MECHANICS OF DEPLOYABLE COILABLE TAPE-SPRINGS

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Declaration

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The above candidate has carried out research for the Masters under my supervision.

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Abstract

Deployable structures play a vital role in a variety of applications such as aerospace structures, rapid development civil engineering projects, medical devices, reconfigurable robotics and many other engineering applications. Deployable thin-walled booms make use of elastic strain energy during storage and are capable of self-deploying to their fully deployed configuration which is an ideal candidate to overcome the bottleneck of limited launch vehicle capacity faced in space applications.

In this research, an attempt has been made to characterise the mechanics of tape spring booms which are the simplest form among the coilable booms. Numerical and analytical frameworks are established to investigate the large deformation analysis of deployable coilable tape springs during the flattening process, which is the initial process of coiling. Geometrically non-linear finite element models implemented in Abaqus/Standard are used to characterize the flattening mechanics of isotropic tape springs under compressive deformation. The effects of geometric and material properties on flattening behaviour are investigated through a numerical parametric study. A simple analytical model is developed to predict the stresses and forces during compression flattening, and a good correlation has been found with the numerical study.

The tension stabilized coiling behaviour of longer tape booms is then investigated through analytical and numerical studies. A useful analytical model is developed to determine the required minimum tension force to prevent instabilities such as blossoming instability and buckling instability. The influence of varying coiling radius due to the thickness of multiple turns is taken into account in the developed analytical framework. Also, the required minimum torque and power for tension stabilized coiling of tape spring are developed considering energy conservation where the effect of friction is also considered.

Coiling of isotropic tape spring booms is simulated in commercially available finite element software Abaqus/Explicit. A good correlation has been found between the numerical and analytical results in terms of the required torque for coiling of longer tape-spring. Furthermore, a novel approach to predict the minimum required tension force to prevent the instabilities is proposed. A numerical parametric study is conducted utilizing this technique in order to study the effect of the coiling ratio on the required tension force. In terms of the bending and tension-dominated regimes, the numerical findings exhibit good qualitative agreement with the established analytical model. Furthermore, a linear trend is observed in the numerical results for the loss of uniqueness region, which is helpful for the development of analytical models.

Keywords: *deployable structures*, *deployable coilable booms*, *tape springs*, *coiling mechanics*, *flattening mechanics*

Dedication

To my parents and sisters, for their unwavering love, support, and inspiration, which have enriched my life and motivated me to pursue and finish this research.

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Nomenclature

List of Abbreviations

ACS3 – Advanced Composites Solar Sail System Technology demonstration mission

CFRP – Carbon Fibre Reinforced Polymer

CLT – Classical laminate theory

CTLT – Composite Thin-walled Lenticular Tube

CTM – Collapsible Tubular Mast

DCB – Deployable Composite Boom

DLR – The German Aerospace Center (German: Deutsches Zentrum für Luft- und Raumfahrt e.V.)

FE – Finite Element

FEA – Finite Element Analysis

FEM – Finite Element Method

FLHD – Four-cell Lenticular Honeycomb Deployable

FRP – Fibre Reinforced Polymer

MARSIS – Mars Advanced Radar for Subsurface and Ionosphere Sounding

NASA – National Aeronautics and Space Administration

NSGA-II – Non-dominated Sorting Genetic Algorithm-II

RVE – Representative Volume Element

SIMPLE – Self-contained Linear Meter-class Deployable

SQP – Sequential Quadratic Programming

STEM – Storable Extendible Tubular Member

TRAC – Triangular Rollable and Collapsible

List of Symbols

ABD	constitutive matrix in coordinate system *x* and *y*
A_{ij}	coefficients of upper-left 3 × 3 submatrix of ABD
A	area of the curved section of the fold
A'	nodal area
B_{ij}	coefficients of upper-right 3 × 3 submatrix of ABD
b	arc length along the cross-section of the tape spring
C	damping coefficient
c_d	dilatational wave speed
c_i	coiling ratio
c_v	viscous pressure coefficient
D_{ij}	coefficients of lower-right 3 × 3 submatrix of ABD
D	bending stiffness of the shell
E	elastic modulus
E'	energy required for the coiling
E_A	artificial strain energy
E_{CD}	energy dissipation due to viscoelasticity or creep
E_E	elastic strain energy
E_{FD}	frictional dissipation energy
E_{KE}	kinetic energy
E_I	internal Energy
E_P	energy dissipation due to inelastic process

E_{VD}	energy absorbed by viscous dissipation
E_W	work done by external forces
E_{Total}	total energy in the system
F_c	flattening force
$(F_c)_{max}$	maximum flattening force
F'	external load on the system
f	flattened length
h	thickness of the tape spring
I	second moment of area of the section
K	stiffness
L	length of the tape spring boom
L'	half of the chord length of tape spring cross-section
l_{min}	shortest length of finite element
L_p	length of the poly region
M	moment per unit length stress resultant
m	mass
M'	moment at the tangential point during the flattening process
N	force per unit length stress resultant
n	number of turns or layers in the coiled tape spring boom
$\boldsymbol{n}$	unit surface normal
p	pressure per unit length
R	transverse radius of the tape spring
r_c	radius of the hub

r_s	fold radius of the tape spring at the secondary stable state
T	required minimum tension force to prevent instabilities
t	time
U	total strain energy per unit length of the shell
U_b	bending energy per unit length of the shell
U_{bs}	bending energy per unit length of the bistable shell at the secondary stable state
U_s	stretching energy per unit length of the shell
u	displacement
u_x	displacement in x direction
$\dot{u}$	velocity
$\ddot{u}$	acceleration
$\boldsymbol{v}$	velocity vector
ν	Poisson's ratio
v_{rel}^{el}	rate of relative motion between the two surfaces
W_T	work done by the applied tension force
W_B	boom bending energy
W_f	work done by friction torque
W_τ	work done by hub torque
x	longitudinal direction
y	transverse direction
z	through thickness direction
α	subtended angle of the tape spring

β	ratio of orthogonal Young's moduli
ϕ	total swept angle by the turns in the coil
δ	deflection
ρ	density
ε^0	mid plane strain
ε_{xx}	longitudinal strain
ε_{yy}	transverse strain
ε_{xy}	shear strain
κ	curvature
κ_{xs}	longitudinal curvature at the secondary stable state
$\Delta\kappa$	curvature change
ω	angular velocity
σ_{xx}	longitudinal stress
$(\sigma_{xx})_{max}$	maximum longitudinal stress
σ_{yy}	transverse stress
$(\sigma_{xx})_{max}$	maximum ransverse stress
σ_{xy}	shear stress
τ_{Hub}	torque required for coiling
$\tau_{f_{hb}}$	torque due to friction between hub and the boom
$\tau_{f_{bb}}$	torque due to friction between the boom itself
ξ	fraction of critical damping in highest frequency mode
μ_0	damping coefficient