SIMULATION OF FOLD-LINE STIFFNESS IN DEPLOYABLE MEMBRANES

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

New designs for space structures such as solar sails and star shades are based on architectures that follow folding and packaging of thin membranes. By leveraging recent advances in origami science, it is possible to design structures in which folded thin membranes deploy following a predetermined and robust path. Design and product optimization of deployable space structures are limited by complex environmental conditions experienced by them. However virtual simulations can be the perfect solution provided proper idealization techniques are followed.

Presence of fold-lines alter the geometrical and mechanical properties of thin membranes which have not being accounted in previous virtual simulations. Two major characteristics identified was the self-opening of the membrane to an equilibrium angle (defined as neutral angle) and the rotational spring stiffness of the membrane at the fold-line.

An experimental study was devised to investigate the variation of fold-line stiffness while varying the neutral angles and membrane thickness for Kapton HN polyimide. A linear empirical relationship between resistive moment and fold-angle is proposed for each thickness.

Self-opening and subsequent unfolding of a single fold was modelled using commercial finite element package, Abaqus/Explicit. Fold-line characteristics were represented with rotational spring connector elements defined between two shell portions. Compared to common idealization approaches (perfect hinge and perfect weld), rotational spring connectors were able to accurately predict the deformation profile and unfolding forces.

Finally, the developed fold idealization technique was applied in an experimental case study of a deploying solar sail. It was shown that neglecting fold-line stiffness underestimate the deploying force of the sail.

Key words: *Folded Membranes; Crease Response; Solar Sails; Finite Element Simulations*

DEDICATION

To my parents, without whom none of this would be possible.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

List of Symbols

ε_{max}	- Fraction of critical damping in highest mode
θ	- Current angle between fold-lines
θ^*	- Folding ratio
υ	- Poisson's ratio
ρ	- Material density
φ	- Neutral angle between fold-lines
ω_{max}	- Highest Eigen value of the model
C_d	- Dilation wave speed
C_v	- Viscous pressure coefficient
D	- Current diameter of the solar sail
D_f	- Initial diameter (before folding) of the solar sail
E	- Young's Modulus
E_f	- Frictional dissipation energy
E_i	- Internal energy (elastic, inelastic, "artificial" strain energy)
E_{ke}	- Kinetic energy
E_{tot}	- Total energy in the system
E_{vd}	- Energy absorbed by viscous dissipation
E_w	- Work of external forces
k	- Gradient of the graph
l	- Membrane length between two folds
L^*	- Characteristic origami length
M	- Resistive moment at the fold-line
n	- Number of sides of a polygon
R_i	- Rotations about i^{th} axis
T	- Tensile load in the membrane due to fold
t	- Time period
U_i	- Translations in i^{th} direction
x	- Distance to the fold-line from the boundary of membrane

List of Abbreviations

CPU	- Central Processing Unit
FEA	- Finite Element Analysis
IKAROS	- Interplanetary Kite-craft Accelerated by Radiation Of the Sun
JAXA	- Japanese Aerospace Exploration Agency
NASA	- National Aeronautics and Space Administration
RP	- Reference Point