# SIMULATION OF FOLD-LINE STIFFNESS IN DEPLOYABLE MEMBRANES



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## DECLARATION

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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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# NOMENCLATURE

## List of Symbols

| | |
|---|---|
| $\varepsilon_{max}$ | - Fraction of critical damping in highest mode |
| $\theta$ | - Current angle between fold-lines |
| $\theta^*$ | - Folding ratio |
| $\upsilon$ | - Poisson's ratio |
| $\rho$ | - Material density |
| $\varphi$ | - Neutral angle between fold-lines |
| $\omega_{max}$ | - 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 |