



Universiteit
Leiden
The Netherlands

Hysterons and pathways in mechanical metamaterials

Ding, J.

Citation

Ding, J. (2023, May 31). *Hysterons and pathways in mechanical metamaterials*. Casimir PhD Series. Retrieved from <https://hdl.handle.net/1887/3619565>

Version: Publisher's Version

[Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

License: <https://hdl.handle.net/1887/3619565>

Note: To cite this publication please use the final published version (if applicable).

Hysterons and Pathways in Mechanical Metamaterials

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof.dr.ir. H. Bijl,
volgens besluit van het college voor promoties
te verdedigen op woensdag 31 mei 2023
klokke 13:45 uur

door

Jiangnan Ding

geboren te Luoyang, China
in 1991

Promotor	Prof. dr. M.L. van Hecke
Co-promotor	Dr. M. Serra-Garcia (Amolf, Amsterdam)
Promotiecommissie	Dr. C. Coulais (University of Amsterdam) Dr.ir. J. T. B. Overvelde (Amolf, Amsterdam) Prof.dr. J. Aarts Prof.dr. D. J. Kraft Prof.dr. T. Schmidt

Casimir PhD series, Delft-Leiden 2023-09

ISBN 978-90-8593-557-5

An electronic version of this thesis can be found at
openaccess.leidenuniv.nl

This work was presented in this dissertation was conducted at AMOLF, Amsterdam, an institute of Netherlands Organisation for Scientific Research (NWO), and the Leiden Institute of Physics, Leiden University. The author was supported by a state scholarship program funded by the China Scholarship Council (CSC).

The cover shows the transition pathways of a biholesy mechanical metamaterial with three hysterons.

To my family.

CONTENTS

1	Introduction	1
1.1	Mechanical metamaterials	1
1.2	Buckling and snapping	5
1.3	Biholey metamaterials	6
1.4	Pathways	9
1.5	Outline of the thesis	12
2	Embedding a mechanical hysteron in a biholesy metamaterial	15
2.1	Motivation	15
2.2	Geometry and approach	17
2.3	Actions of the beam controlled by geometry	19
2.4	Interpretation: boundary conditions of the defect beam . . .	22
2.5	Appropriate design for snapping	23
2.6	Conclusion	25
3	Sequential snapping and pathways in a biholesy metamaterial	27
3.1	Introduction and motivation	27
3.2	Phenomenology	29

3.3	Geometry and approach	31
3.4	(Un)snapping in biholey metamaterial	35
3.5	Transition pathways and states	37
3.6	Tuning pathways by tilting	39
3.7	Non-hysteron degrees of freedom	43
3.8	Conclusion	48
<i>Appendix</i>	49
3.A	Tuning ε^\pm by additional pushers	49
3.B	Detachable hysterons and composite samples	51
4	Pathways and emergent hysterons in programmable mechanical metamaterials	55
4.1	Introduction	55
4.2	Geometry, fabrication, experimental protocol	57
4.3	Controlling the switching field of a single hysteron with a single clamp	60
4.4	Two emergent hysterons	62
4.5	Programming the pathways	63
4.6	Hysteron Interactions	66
4.7	Tilting	72
4.8	Sample with three hysterons and outlook	75
4.9	Conclusion	78
5	Pattern formation, frustration, and the first unstable mode of a monoholar mechanical metamaterial	79
5.1	Introduction	79
5.2	Phenomenology	80
5.3	Numeric procedure: Pattern tracking and flattening	82
5.4	The First Unstable Mode in Monoholar Samples	83

5.5 Scrambling and cooperating of the regimes	90
5.6 Conclusion	96
A Appendix	97
A.1 Molding	97
A.2 Sample Preparation	99
A.3 Experimental Protocol	102
A.4 FEM analysis and the type of element	105
Summary	117
Samenvatting	121
Publications	125
Curriculum Vitae	127
Acknowledgment	129