



Universiteit
Leiden
The Netherlands

Strategies for mechanical metamaterial design

Singh, N.

Citation

Singh, N. (2019, April 10). *Strategies for mechanical metamaterial design*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/71234>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/71234>

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

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/71234> holds various files of this Leiden University dissertation.

Author: Singh, N.

Title: Strategies for mechanical metamaterial design

Issue Date: 2019-04-10

Strategies for Mechanical Metamaterial Design

PROEFSCHRIFT

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op woensdag 10 April 2019
klokke 15:00 uur

door

Nitin Singh

geboren te Barnala, India

in 1991

PROMOTOR

prof. dr. M.L. van Hecke

PROMOTIECOMMISSIE

prof. dr. M. Dijkstra (*Universiteit Utrecht*)

dr. J.T.B. Overvelde (*AMOLF, Amsterdam*)

prof. dr. E.R. Eliel

prof. dr. J.M. van Ruitenbeek

NEDERLANDSE TITEL

Strategieën voor mechanische metamateriaalontwerp.

Casimir PhD series, Delft-Leiden, 2019-08

ISBN 978-90-8593-389-2

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

The work presented in this thesis was conducted mainly at the NWO institute AMOLF, Amsterdam and partially at the Leiden Institute of Physics (LION), Leiden University and is part of an industrial partnership programme (IPP) ‘*Computational Sciences for Energy Research (CSER)*’ started jointly in 2012 by the Shell Global Solutions International B.V., the Netherlands Organization for Scientific Research (NWO) and the Foundation for Fundamental Research on Matter (FOM).

For my family.

Contents

1	Introduction	7
1.1	Introduction	7
1.2	Inverse Strategies for Material Design	11
1.3	Outline of the Thesis	14
2	The Soft Mechanism	17
2.1	Introduction	18
2.2	Soft Mechanism Model	21
	2.2.1 Load-Deformation Response	22
	2.2.2 Internal Energy of the System	26
2.3	Geometrical Interpretation	29
	2.3.1 Mechanical Regimes from Geometrical Viewpoint . .	33
	2.3.2 A General Design Strategy	41
2.4	Soft Mechanism with Torsional Springs	42
2.5	Weak Symmetry Breaking in Monoholar Systems	46
	2.5.1 Soft Mechanism for a Perturbed Monoholar System	51
	2.5.2 Perfect Pitchfork Bifurcation	56
2.6	Conclusions	58
3	Rational Design of Flexible Yet Generic 2D Mechanical Metamaterials	61
3.1	Introduction	62
3.2	Mathematical Loop Condition	69
3.3	Numerical Model	73
	3.3.1 Energy Functional	74
	3.3.2 Energy Minimization	76

3.4	Design Problem Formulation	78
3.4.1	Design Variables	79
3.4.2	Objective Function and Constraint Handling	81
3.5	PSO and Implementation Details	87
3.5.1	Particle Swarm Optimization (PSO)	88
3.5.2	Implementation of PSO	92
3.6	Parameter Selection for Optimum Search	95
3.6.1	Hyperparameter Optimization	95
3.6.2	Distribution of Final Solutions	99
3.7	Visualization of the Search Process	102
3.8	Results	107
3.8.1	Validation of the Local Minimum	108
3.8.2	Validating Across Large Statistics	114
3.9	A Proof of Concept with 3D Printing	120
3.9.1	Unit Cells	121
3.9.2	Metatilings	122
3.10	Discussion and Conclusion	124
4	Rational Design of Multi-stable 2D Mechanical Metamaterials	127
4.1	Introduction	128
4.2	Characterizing the Performance of PSO	131
4.3	Optimized Mechanisms	137
4.4	A Proof of Concept with 3D Printing	143
4.4.1	Unit Cells	146
4.4.2	Metatilings	149
4.5	Discussion and Conclusion	154
	Summary	157
	Samenvatting	161
	Publication List	165
	Curriculum Vitae	167
	Acknowledgments	169
	Bibliography	171