

University of Groningen

## Nature-inspired microfluidic propulsion using magnetic artificial cilia

Khaderi, Syed Nizamuddin

**IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.**

*Document Version*

Publisher's PDF, also known as Version of record

*Publication date:*

2011

[Link to publication in University of Groningen/UMCG research database](#)

*Citation for published version (APA):*

Khaderi, S. N. (2011). *Nature-inspired microfluidic propulsion using magnetic artificial cilia*. s.n.

### Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

### Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

*Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.*

# Nature-inspired microfluidic propulsion using magnetic artificial cilia

Syed Nizamuddin Khaderi

# **Nature-inspired microfluidic propulsion using magnetic artificial cilia**

Syed Nizamuddin Khaderi

PhD Thesis  
University of Groningen  
The Netherlands



University of Groningen  
**Zernike Institute  
for Advanced Materials**

Zernike Institute for Advanced Materials

ISBN: 978-90-367-5072-1

This work is part of the 6<sup>th</sup> Framework European Union project ‘Artic’, under contract STRP 033274.

RIJKSUNIVERSITEIT GRONINGEN

**Nature-inspired microfluidic propulsion  
using magnetic artificial cilia**

Proefschrift

ter verkrijging van het doctoraat in de  
Wiskunde en Natuurwetenschappen  
aan de Rijksuniversiteit Groningen  
op gezag van de  
Rector Magnificus, dr. E. Sterken,  
in het openbaar te verdedigen op  
vrijdag 16 september 2011  
om 13.15 uur

door

**Syed Nizamuddin Khaderi**

geboren op 22 oktober 1982  
te Chennai, India

Promotor: Prof. dr. ir. P. R. Onck

Beoordelingscommissie: Prof. dr. S. Verpoorte  
Prof. dr. R. Superfine  
Prof. dr. H. Gao

To my parents



---

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Lab-on-a-chip . . . . .	1
1.2	Micron-scale fluid manipulation in nature . . . . .	2
1.3	Structure of cilia and flagella . . . . .	4
1.4	Hydrodynamics at small length scales . . . . .	4
1.5	Objective of the thesis . . . . .	5
1.6	Thesis outline . . . . .	6
<b>2</b>	<b>Magneto-mechanical model</b>	<b>9</b>
2.1	Introduction . . . . .	9
2.2	Equations of motion . . . . .	10
2.2.1	Solid dynamics model . . . . .	10
2.2.2	Fluid dynamics model . . . . .	10
2.2.3	Fluid-structure interaction . . . . .	12
2.2.4	Magnetostatics . . . . .	13
2.3	Dimensional analysis . . . . .	15
<b>3</b>	<b>Asymmetric configurations</b>	<b>19</b>
3.1	Introduction . . . . .	19
3.2	Results . . . . .	20
3.2.1	Partly magnetic film with cracks. . . . .	20
3.2.2	Buckling of a straight magnetic film . . . . .	21
3.2.3	Curled permanently magnetic film . . . . .	22
3.2.4	Super-paramagnetic film . . . . .	23
3.2.5	Fluid propelled . . . . .	24
3.2.6	Parametric study . . . . .	25
3.3	Summary . . . . .	26
<b>4</b>	<b>Effect of cilia spacing and channel height</b>	<b>29</b>
4.1	Introduction . . . . .	29
4.2	Computational model . . . . .	31
4.3	Results and discussion . . . . .	32



---

4.3.1	Closed-loop channel . . . . .	33
4.3.2	Open-loop channel . . . . .	34
4.4	Conclusions . . . . .	38
<b>5</b>	<b>Inertial effects in ciliary flows - artificial cilia</b>	<b>39</b>
5.1	Introduction . . . . .	39
5.2	Results . . . . .	40
5.2.1	Uniform magnetic field: effect of fluid inertia . . . . .	40
5.3	Conclusion . . . . .	50
<b>6</b>	<b>Inertial effects in ciliary flows - model problem</b>	<b>51</b>
6.1	Introduction . . . . .	51
6.2	Problem definition . . . . .	52
6.3	Results . . . . .	53
6.3.1	Effect of spatial and temporal asymmetry . . . . .	53
6.3.2	Effect of orientational asymmetry . . . . .	55
6.4	Configurational symmetry . . . . .	57
6.5	Summary . . . . .	57
<b>7</b>	<b>Effect of metachronal waves</b>	<b>59</b>
7.1	Introduction . . . . .	59
7.2	Results . . . . .	62
7.2.1	Externally imposed out-of-phase motion . . . . .	62
7.2.2	Out-of-phase motion caused by a non-uniform magnetic field . . . . .	71
7.3	Conclusions . . . . .	75
<b>8</b>	<b>Fluid flow caused by collective non-reciprocal motion</b>	<b>79</b>
8.1	Introduction . . . . .	79
8.2	Problem definition . . . . .	80
8.3	Results . . . . .	82
8.3.1	Collective non-reciprocal motion . . . . .	82
8.3.2	The fundamental mechanism . . . . .	82
8.3.3	Parametric study . . . . .	85
8.4	Conclusions . . . . .	89
<b>9</b>	<b>Three-dimensional numerical model</b>	<b>91</b>
9.1	Introduction . . . . .	91
9.2	Formulation . . . . .	93
9.2.1	Solid mechanics model . . . . .	93
9.2.2	Fluid dynamics model . . . . .	97
9.2.3	Solid-fluid coupling . . . . .	98
9.2.4	Magneto-static model . . . . .	98
9.3	Applications of the coupled magneto-mechanical model . . . . .	99
9.3.1	Motion of a cilium with non-uniform width . . . . .	99
9.3.2	Effect of the cilia width and spacing . . . . .	102
9.3.3	Effect of metachronal waves in the out-of-plane direction . . . . .	103

9.3.4	Out-of-plane actuation of cilia . . . . .	106
9.4	Summary . . . . .	106
<b>10</b>	<b>Summary</b>	<b>111</b>
<b>Appendices</b>		<b>115</b>
A	Solid dynamics model . . . . .	117
B	Discretisation of various terms used in section 2.2 . . . . .	118
C	Magnetic field caused by a magnetic segment . . . . .	120
D	Validation of the magneto-static model . . . . .	120
E	Validation of the fluid-structure interaction model . . . . .	121
F	Convergence of the numerical model . . . . .	121
G	Effect of diffusion Reynolds number - analytical model . . . . .	124
H	Resistive force theory . . . . .	127
I	Magnetic buckling analysis . . . . .	128
J	Metachronal wave velocity . . . . .	129
K	Calculation of the net pressure gradient . . . . .	130
L	Benchmark tests for the 3D model . . . . .	132
<b>Samenvatting</b>		<b>135</b>
<b>Bibliography</b>		<b>139</b>
<b>List of publications</b>		<b>149</b>
<b>Acknowledgements</b>		<b>151</b>

