



## **Control and Optimization of a Lorentz Force Based Actuator System for External Flow**

Martin Florian Seidler

Energie & Umwelt / Energy & Environment

Band / Volume 524

ISBN 978-3-95806-518-5

Forschungszentrum Jülich GmbH  
Zentralinstitut für Engineering, Elektronik und Analytik (ZEA)  
Systeme der Elektronik (ZEA-2)

# **Control and Optimization of a Lorentz Force Based Actuator System for External Flow**

Martin Florian Seidler

Schriften des Forschungszentrums Jülich  
Reihe Energie & Umwelt / Energy & Environment

Band / Volume 524

---

ISSN 1866-1793

ISBN 978-3-95806-518-5

# Contents

<b>Abbreviations</b>	<b>xi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Research Unit FOR 1779 . . . . .	2
1.2 System Requirements . . . . .	3
1.3 Thesis Overview . . . . .	5
<b>2 Lorentz Force Actuator System</b>	<b>9</b>
2.1 Mechanical Properties . . . . .	9
2.2 Lorentz Force . . . . .	12
2.3 Actuator System 1.0 . . . . .	13
2.4 Actuator System 2.0 . . . . .	15
2.5 Classification and Comparison to MAKOS . . . . .	18
2.6 Summary . . . . .	19
<b>3 Software Tool Chain and General Purpose Hardware</b>	<b>21</b>
3.1 Simulink . . . . .	21
3.2 Speedgoat . . . . .	24
3.3 COMSOL . . . . .	25
3.4 Altium . . . . .	26
3.5 Inventor . . . . .	26
3.6 3D Printer . . . . .	27
3.7 Three Bar System . . . . .	28
3.8 Reference Sensors . . . . .	29
3.9 Summary . . . . .	31
<b>4 System Models and System Upgrades</b>	<b>33</b>
4.1 Model from First Principles . . . . .	33
4.1.1 Reset Force . . . . .	35
4.1.2 Hysteresis . . . . .	39

4.1.3	Inductive coupling between the coils . . . . .	40
4.1.4	Rotational Oscillations . . . . .	41
4.2	Online Sensors . . . . .	43
4.2.1	Hall Sensors . . . . .	43
4.2.2	Light Barrier Sensors . . . . .	46
4.3	Power Amplifier . . . . .	49
4.4	Ampacity of the Actuator Coils . . . . .	52
4.5	Utility Upgrades in System 2.1 . . . . .	55
4.6	Summary . . . . .	56
<b>5</b>	<b>Control Design</b>	<b>59</b>
5.1	Proportional Derivative Control . . . . .	60
5.1.1	Transfer Function for One Bar . . . . .	60
5.1.2	PD Control Design . . . . .	60
5.2	Multiple Input Multiple Output State Space Model . . . . .	62
5.2.1	Greybox Model Identification . . . . .	64
5.3	Iterative Learning Control . . . . .	67
5.3.1	Gain Switching ILC . . . . .	70
5.3.2	ILC Implementation on the Three Bar System . . . . .	72
5.4	Zero Level Control . . . . .	76
5.4.1	Collective Control . . . . .	76
5.4.2	Dead Zone PI . . . . .	77
5.5	Single Frequency Model . . . . .	80
5.6	Decoupling Steering . . . . .	82
5.7	Final Control Design . . . . .	85
5.8	Summary . . . . .	88
<b>6</b>	<b>Verification of System 2.1</b>	<b>89</b>
6.1	Reference Tracking Tests . . . . .	89
6.1.1	Parameter Transition . . . . .	90
6.2	Wind Tunnel Performance Test . . . . .	93
6.2.1	Wind Tunnel Setup . . . . .	93
6.2.2	Results of the Measurements . . . . .	96
6.3	Implementation Requirement Fulfillment . . . . .	98
6.4	Summary . . . . .	103
<b>7</b>	<b>Actuator System 3.x Development</b>	<b>105</b>
7.1	Actuator 3.x Concept . . . . .	105

7.2 FEM Aided Performance Improvement . . . . .	108
7.2.1 Static Magnetic Flux . . . . .	109
7.2.2 Losses and Heat removal . . . . .	112
7.3 The 3.x Prototypes . . . . .	113
7.3.1 Performance of System 3.0 . . . . .	116
7.3.2 Full-Scale System 3.1 . . . . .	121
7.4 Summary . . . . .	123
<b>8 Conclusion and Outlook</b>	<b>125</b>
<b>Curriculum Vitae</b>	<b>129</b>
<b>Bibliography</b>	<b>131</b>

Energie & Umwelt / Energy & Environment  
Band / Volume 524  
ISBN 978-3-95806-518-5

Mitglied der Helmholtz-Gemeinschaft

