

**Shape Optimization for Fluids Using T-Splines for  
Shape Representation and Stabilized Finite Elements  
for the Fluid Flow Simulations**

Von der Fakultät für Maschinenwesen  
der Rheinisch-Westfälischen Technischen Hochschule Aachen  
zur Erlangung des akademischen Grades eines  
Doktors der Ingenieurwissenschaften  
genehmigte Dissertation

vorgelegt von:

Mike Nicolai

Berichter: Universitätsprofessor Marek Behr, Ph.D.  
Universitätsprofessor Dr.-Ing. Jörg Feldhusen  
Tag der mündlichen Prüfung: 16.7.2012

---

# Contents

Acknowledgments . . . . .	v
Contents . . . . .	vii
<b>Introduction</b>	<b>1</b>
<b>1 Shape Optimization For Fluid Flows</b>	<b>9</b>
1.1 PDE-constrained optimization . . . . .	9
1.2 Shape optimization problem . . . . .	13
1.2.1 Formulation of the shape optimization problem	13
1.2.2 Gradients in the NAND approach . . . . .	18
1.3 Governing equations . . . . .	21
1.3.1 Physical fluid flow model . . . . .	21

1.3.2	Mesh deformation . . . . .	25
1.4	Problem formulation . . . . .	26
1.5	Software overview . . . . .	28
<b>2</b>	<b>Finite Element Problem Formulation</b>	<b>31</b>
2.1	Modified flow solver . . . . .	32
2.1.1	Solution method . . . . .	35
2.2	Finite elements for the mesh equation . . . . .	38
2.3	Finite elements for the flow equations . . . . .	42
2.3.1	GLS stabilized finite elements . . . . .	44
2.4	Sensitivity of the isoparametric transformation . . . . .	48
2.5	The stabilization parameter . . . . .	50
2.5.1	Stabilization after Shakib . . . . .	51
2.5.2	SUPG+PSPG stabilization . . . . .	52
<b>3</b>	<b>Optimization Methods</b>	<b>55</b>
3.1	Discrete optimization: graph partitioning . . . . .	57
3.2	Continuous optimization: nonlinear programming . . . . .	59
3.2.1	Damped steepest descent . . . . .	60
3.2.2	Quasi-Newton with line search . . . . .	61

3.2.3	Nelder-Mead simplex search . . . . .	63
3.2.4	Gradient-free trust-region . . . . .	65
3.2.5	Genetic algorithm . . . . .	66
3.2.6	DIRECT Lipschitz optimization . . . . .	67
3.3	Benchmark problems . . . . .	71
3.3.1	Quadratic function . . . . .	71
3.3.2	Rosenbrock function . . . . .	72
3.3.3	Judge function . . . . .	73
3.3.4	Rastrigin function . . . . .	77
3.4	Conclusion . . . . .	79
<b>4</b>	<b>Surface Representation</b>	<b>81</b>
4.1	Surface representation using B-splines . . . . .	83
4.1.1	B-spline and NURBS . . . . .	83
4.1.2	Basis functions . . . . .	84
4.1.3	NURBS surfaces . . . . .	88
4.2	Point-based splines . . . . .	90
4.3	T-splines . . . . .	91
4.3.1	T-mesh . . . . .	93
4.3.2	T-spline evaluation . . . . .	96

## Contents

---

4.4	Shape parameterization . . . . .	99
4.4.1	Control point dependence . . . . .	101
4.4.2	Shape gradient . . . . .	101
4.5	Conclusion . . . . .	103
<b>5</b>	<b>Method Performance and Validation</b>	<b>105</b>
5.1	Laminar pipe flow . . . . .	106
5.1.1	Two-dimensional pipe flow . . . . .	109
5.1.2	Three-dimensional pipe flow . . . . .	110
5.1.3	Parallel performance of the laminar pipe . . .	111
5.2	Validation using an artificial graft . . . . .	114
5.2.1	Gradient validation by detecting the minimum	115
5.2.2	Influence of remeshing on the optimal result .	116
5.2.3	Influence of mesh deformation on the optimal result . . . . .	119
5.2.4	Influence of stabilization on optimal result .	119
5.3	Conclusion . . . . .	124
<b>6</b>	<b>Shape Optimization Test Cases</b>	<b>125</b>
6.1	Artificial graft optimization . . . . .	126
6.1.1	Two-dimensional artificial graft optimization	129

6.1.2	Three-dimensional artificial graft optimization	132
6.2	Extrusion die optimization . . . . .	140
6.2.1	Three-dimensional extrusion die optimization	141
6.3	Conclusion . . . . .	144
7	Summary and outlook	147
A	Isoparametric transformation sensitivities	151
B	Gradient of the stabilization term	157
C	Discrete mesh equations	159
D	Discrete flow equations	161
	Bibliography	167