Design of Auxetic Stents by Topology Optimization

by Huipeng Xue

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of A/Prof Zhen Luo and Dr. Terry Brown

University of Technology Sydney
Faculty of Engineering and Information Technology

October 2020

Title of the thesis:

Design of Auxetic Stents by Topology Optimization

Ph.D. student:

Huipeng Xue

E-mail: **huipeng.xue@student.uts.edu.au**

Supervisor:

A/Prof Zhen Luo

E-mail: **zhen.luo@uts.edu.au**

Co-Supervisor:

Dr. Terry Brown

E-mail: **terry.brown@uts.edu.au**

Address:

School of Mechanical and Mechatronic Engineering

The University of Technology Sydney, Sydney, NSW 2007, Australia

Certificate of Original Authorship

I, Huipeng Xue declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical & Mechatronic Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature of Student:

Production Note:
Signature removed prior to publication.

HUIPENG XUE

Date: 16/10/2020

Acknowledgments

I would like to take this opportunity to express my deep gratitude to all those who helped me throughout my candidature.

First and foremost, I would like to extend my sincere gratitude to my principal supervisor, A/Prof. Z Luo. During the studying of the course and the writing of the thesis, he had contributed greatly by giving useful suggestions and constructive criticism. He devoted a considerable portion of his time to reading my manuscripts and making suggestions for further revisions. Moreover, he gave me many encouragements and other help in my study and life. Also, I would like to express my heartfelt gratitude to my co-supervisor Terry Brown and my technical instructor Dr. Jindong Yang for their support and guidance. Their outstanding knowledge, intelligence and wisdom have a profound influence on me.

I also wish to express my gratitude to Dr. Hao Li and Dr. Yu Wang. They offered me great help and gave me many valuable suggestions. My sincere thanks should also go to my colleagues Jing Zheng, Jie Gao, Shuhao Wu, Xianfeng Man and Zuyu Li for their support.

My last and special thanks would go to my beloved family for their loving considerations and great confidence in me all through these years.

Huipeng Xue

Sydney, 2020

Publications and Conference Contributions

International scientific journal publications:

[1] **H. Xue**, Z. Luo, T. Brown, & S. Beier, Design of Self-Expanding Auxetic Stents Using Topology Optimization. Frontiers in Bioengineering and Biotechnology, 2020. 8: p. 736.

[2] J. Gao, **H. Xue**, L. Gao, & Z. Luo, Topology optimization for auxetic metamaterials based on isogeometric analysis. Computer Methods in Applied Mechanics and Engineering, 2019. 352: p. 211-236.

[3] **H. Xue**, Z. Luo, S. Beier, & B. Halkon, Design of Self-Expanding Auxetic Coronary Stents by Considering Hemodynamics Using Topology Optimization. IEEE Transactions on Biomedical Engineering, about to be submitted.

International scientific book section:

[4] **H. Xue**, & Z. Luo, Design of Auxetic Coronary Stents by Topology Optimization, in Computational Biomechanics for Medicine. 2019, Springer. 17-31.

International conference publications:

[5] **H. Xue**, & Z. Luo, Negative Poisson's Ratio Design of the Cardiovascular Stent

Using a Level Set-based Parameterization Method. In: The 13th World Congress on Computational Mechanics (WCCM 2018), New York.

[6] **H. Xue**, P. Johal, Z. Luo, & T. Brown, Design of Auxetic Coronary Stents Using Topological Optimization. In: The 13th World Congress of Structural and Multidisciplinary Optimization (WCSMO 13), Beijing.

List of Figures

Figure 2-1 A typical bare-metal stent 8

Figure 2-2 A typical drug-eluting stent 10

Figure 2-3 Two typical stenting structures 17

Figure 2-4 A parametric strut for optimization 18

Figure 2-5 Blood obstruction of stent strut 20

Figure 3-1 A 2D boundary representation by 3D level set surface 42

Figure 3-2 Supported domain of knot *i* with radius d_{mI} 45

Figure 3-3 A 2D boundary representation by 3D level set surface 46

Figure 3-4 Level set function in curvilinear coordinates 48

Figure 4-1 An illustration of homogenization 53

Figure 4-2 The flowchart of the concurrent topology optimization 61

Figure 4-3 (A) Macro analysis domain; (B) micro design domain 63

Figure 4-4 The optimization of 35% volume fraction: (A) Initial design; (B–E) four intermediate results; (F) final design 64

Figure 4-5 The convergences of 35% volume fraction 65

Figure 4-6 The optimization of 25% volume fraction: (A) Initial design; (B–E) four intermediate results; (F) final design 65

Figure 4-7 The convergences of 25% volume fraction. 66

Figure 4-8 The optimization of 20% volume fraction: (A) Initial design; (B–E) four intermediate results; (F) final design 66

Figure 4-9 (A) The convergences of 20% volume fraction. 67

Figure 4-10 The final numerical design result 67

Figure 4-11 The geometry of the optimized stent 68

Figure 4-12 (A) Compression test; (B) Stretching test 71

Figure 4-13 Stent expansion test 72

Figure 4-14 The prototype of the optimized auxetic stent 73

Figure 5-1 Flow pattern in the design domain 81

Figure 5-2 The 3D computational domain 83

Figure 5-3 The flowchart of the topology optimization 102

Figure 5-4 Multi-domain of the numerical model 103

Figure 5-5 The optimization of E-6: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 124

Figure 5-6 The convergent histories of E-6. 124

Figure 5-7 The optimization of E-7: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 126

Figure 5-8 The convergent history of E-7. 126

Figure 5-9 The optimization of E-8: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 127

Figure 5-10 The convergent history of E-8. 127

Figure 5-11 The optimization of F-6: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 133

Figure 5-12 The convergent history of F-6. 133

Figure 5-13 The optimization of F-7: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 134

Figure 5-14 The convergent history of F-7. 135

Figure 5-15 The optimization of F-8: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 136

Figure 5-16 The convergent history of F-8. 136

Figure 5-17 The optimization of G-6: (A) Initial design; (B-E) Four intermediate results; (F) Final design. 141

Figure 5-18 The convergent history of G-6. 141

Figure 5-19 The optimization of G-7: (A) Initial design; (B-E) Four intermediate results;

(F) Final design. 142

Figure 5-20 The convergent history of G-7. 142

Figure 6-1 The geometry of F-7. 146

Figure 6-2 The Compression test for F-7. 147

Figure 6-3 The geometry of F-8. 148

Figure 6-4 The Compression test for F-8. 148

Figure 6-5 The geometry of G-7. 149

Figure 6-6 The Compression test for G-7. 149

Figure 6-7 The deformation results of the axial compression test. 151

Figure 6-8 The CFD model for the stent F-7. 152

Figure 6-9 The streamlines of blood around the stent F-7. 153

Figure 6-10 The streamlines of blood around the proximal struts of the stent F-7....... 155

Figure 6-11 The streamlines of blood around the distal struts of the stent F-7............ 155

Figure 6-12 Axial WSS of the stent F-7. 156

Figure 6-13 The streamlines of blood around the stent F-8. 158

Figure 6-14 The streamlines of blood around the proximal struts of the stent F-8....... 159

Figure 6-15 The streamlines of blood around the distal struts of the stent F-8. 159

Figure 6-16 The distributions of WSS of the stent F-8. 160

Figure 6-17 The streamlines of blood around the stent G-7. 161

Figure 6-18 The streamlines of blood around the proximal struts of the stent G-7. 162

Figure 6-19 The streamlines of blood around the distal struts of the stent G-7........... 162

Figure 6-20 The distributions of WSS of the stent G-7. 163

List of Tables

Table 2-1 The impact of WSS magnitude on the stent region..21

Table 5-1 The results of various weight factor W_3 in a range of (10-80%)...................106

Table 5-2 The results of various weight factor W_2 in a range of (10-80%)...................109

Table 5-3 The results of various weight factor W_1 in a range of (10-80%)...................112

Table 5-4 The results(W_3=30%) of various weight factor W_1 and W_2...........................115

Table 5-5 The results of various volume fractions for 45%-25%-30%.........................120

Table 5-6 The effective elasticity tensor and modified permeability of E-6, 7,8..........123

Table 5-7 The NPRs and vertical Permeability of E-6, 7, 8...123

Table 5-8 The results of various volume fractions for 40%-30%-30%.........................129

Table 5-9 The effective elasticity tensor and modified permeability of F-6, 7, 8.........131

Table 5-10 The NPRs and vertical Permeability of F-6, 7, 8.......................................131

Table 5-11 The results of various volume fractions for 35%-35%-30%.......................138

Table 5-12 The effective elasticity tensor and modified permeability of G-6, 7..........140

Table 5-13 The NPRs and vertical Permeability of G-6, 7..140

Table 6-1 The WSS results of the three optimized stents..164

Abbreviations

BE	Balloon-expandable
BESO	Bi-directional Evolutionary Structural Optimization
BMS	Bare-metal stent
BVS	Bioresorbable vascular scaffolds
CAD	Coronary artery disease
CFD	Computational fluid dynamics
CFL	Courant–Friederichs–Lewy
CoCr	Cobalt-chromium
CSRBF	Compactly supported radial basis function
CT	Computed tomography
DAPT	Dual antiplatelet therapy
DES	Drug-eluting stents
ESO	Evolutionary structural optimization
FDA	Food and Drug Administration
FEA	Finite element analysis
FSI	Fluid-structure interaction
HJ-PDE	Hamilton-jacobian partial derivative equation
ISR	In-stent restenosis

IVUS	Intravascular ultrasound
LSM	Level set method
MFP	Modified fluid permeability
MMC	Moving morphable components
NIH	Neointimal hyperplasia
NPR	Negative Poisson' ratio
NS	Naiver-stokes
OC	Optimality criteria
OCT	Optical coherence tomography
ODE	Ordinary differential equation
PCI	Percutaneous coronary intervention
PLSM	Parametric level set method
PtCr	Platinum-chromium
SE	Self-expanding
SIMP	Solid Isotropic Material with Penalization
ST	Stent thrombosis
TAWSS	Time-averaged wall shear stress
WSS	Wall shear stress
WSSG	Wall shear stress gradient
X-PLSM	Extended parametric level set method

Abstract

As high efficiency and minimal invasive, percutaneous coronary intervention with stents is a popular treatment for coronary artery disease but suffering from the risks of stent thrombosis and in-stent restenosis. Apart from the biological factors, stenting structures have been demonstrated to have strong associations with the incidences of these complications. The impacts of stenting structures mainly concern two aspects, the mechanical failures, and the induced hemodynamic changes. This thesis introduces mechanical metamaterials and topology optimization into stent design to overcome the limitations. As a kind of artificially engineered metamaterials, the auxetic material with unique mechanical properties due to the effective negative poison’s ratio is incorporated into the stent design to overcome mechanical failures of the conventional stenting structures. Based on the auxetics, a multiscale topology optimization method is developed to generate auxetic stenting structures to enhance their mechanical performances. Additionally, a modified fluid permeability is proposed to quantify the stent induced obstructions to the blood flow. It successfully combines hemodynamic considerations into the developed topology optimization design for stents.

Chapter 1 provides a brief introduction to this research. Chapter 2 gives the background and a comprehensive literature review, including different coronary stents, the mechanical and hemodynamic factors of the complications, the stenting optimization, topology optimization, multifunctional artificial cellular composites, and auxetic metamaterials.

In Chapter 3, an extended parametric level set method (X-PLSM) is proposed to transform the parametric level set method (PLSM) from the cartesian coordinate system to a curvilinear system. Thus, the X-PLSM can implicitly represent the boundaries of shell structures efficiently rather than using the conventional PLSM for 3D models, which can benefit the design of stents.

In Chapter 4, a multiscale topology optimization based on X-PLSM is developed to introduce auxetics into the design of self-expanding (SE) stents, aiming to enhance the stenting performances and overcome their mechanical failures. Then, the optimized auxetic SE stent is numerically validated in software ANSYS and prototyped using additive manufacturing techniques.

In Chapter 5, a modified fluid permeability (MFP) is proposed to quantify the stent induced obstructions to the blood flow. After that, a multiscale multi-objective topology optimization based on PLSM is developed and performed to introduce the auxetic properties, maximize macroscopic stiffness, and minimize the stent induced obstructions. During the optimization, the impacts of each design objective function on the stenting structures are discussed.

In Chapter 6, the deformation mechanism of the optimized stents and the surrounding blood flow is numerically simulated in ANSYS and CFX, respectively.

Finally, conclusions and prospects are provided in Chapter 7.

Contents

Certificate of Original Authorship I

Acknowledgments II

Publications and Conference Contributions III

List of Figures V

List of Tables VIII

Abbreviations IX

Abstract XI

Contents i

Chapter 1 Introduction 1

1.1 Overview of the project 1

1.2 Research contributions 3

1.3 Outline of the thesis 5

Chapter 2 Literature review 7

2.1 Coronary artery stents 7

2.1.1 Bare-metal stents (BMS) 7

2.1.2 Drug-eluting stents (DES) 9

2.1.3 Bioresorbable vascular scaffolds (BVS) 11

2.1.4 Balloon-expandable (BE) and self-expanding (SE) mechanism 12

2.2 Mechanical factors in stent design 14

2.2.1 Mechanical failures 15

2.2.2 Stent designs 16

2.3 Hemodynamics in stent design 19

2.3.1 Metrics of hemodynamics 20

2.3.2 Investigations of stent strut geometries 23

2.3.3 CFD models 25

2.3.4 Stent optimization by CFD 27

2.4 Topology optimization 30

2.4.1 Topology optimization methods..31

2.4.2 Topological design of microstructural metamaterials 36

2.5 Auxetic metamaterials..38

2.6 Summary for the literature review and the research gaps 39

Chapter 3 Extended parametric level set method (X-PLSM) 41

3.1 Conventional Level set method (LSM)..41

3.1.1 Boundary representation 41

3.1.2 Hamilton-Jacobi equation 42

3.2 Parametric level set method (PLSM) 44

3.2.1 Compactly supported radial basis functions (CSRBFs)........................44

3.2.2 Parameterization of the level set function..46

3.3 Extended parametric level set method (X-PLSM)..47

3.4 Conclusion 50

Chapter 4 Topology optimization of auxetic stents considering structural performance..51

4.1 Numerical homogenization method 53

4.2 Shell elements 55

4.3 Optimization model and sensitivity analysis..55

4.3.1 Optimization model..56

4.3.2 Sensitivity analysis..59

4.3.3 Numerical procedural..61

4.4 Examples and discussion 62

4.4.1 The result of 35% volume 63

4.4.2 The result of 25% volume 65

4.4.3 The result of 20% volume 66

4.5 Numerical validation by ANSYS 68

4.5.1 Auxetic behavior 69

4.5.2 Simulation of inadequate expansion and malapposition 71

4.6 3D printing 72

4.7 Conclusion 74

Chapter 5 Hemodynamic optimization of auxetic stents 76

5.1 Assumptions and design domain 77

5.1.1 Assumptions 77

5.1.2 Computational model and design domains 82

5.2 Darcy-Stokes model applied in the microscale 84

5.2.1 Stokes flow 85

5.2.2 Darcy flow 87

5.2.3 Darcy-Stokes coupling 88

5.3 Homogenization of the stent properties 89

5.3.1 Homogenization of elasticity 90

5.3.2 Homogenization of modified fluid permeability (MFP) 91

5.4 Optimization model and sensitivity analysis 93

5.4.1 Optimization model 94

5.4.2 Sensitivity analysis 98

5.4.3 Numerical Procedure 101

5.5 Examples and discussion 102

5.5.1 Studies of three weight factors 105

5.5.2 Studies of varying volume fractions 119

5.5.3 Discussion 143

Chapter 6 Numerical validation for the hemodynamic optimized auxetic stents 145

6.1 Validation of auxetic deformation behaviors 145

6.1.1 The radial compression tests 146

6.1.2 The axial compression tests 150

6.2 Blood flow in the stented segment 152

6.2.1 Fluid validations for F-7 152

6.2.2 Fluid validations for F-8 157

6.2.3 Fluid validations for G-7 160

6.3 Discussion and conclusion 163

Chapter 7 Conclusion and prospect 166

7.1 Summary 166

7.2 Prospect for future works 169

References 171