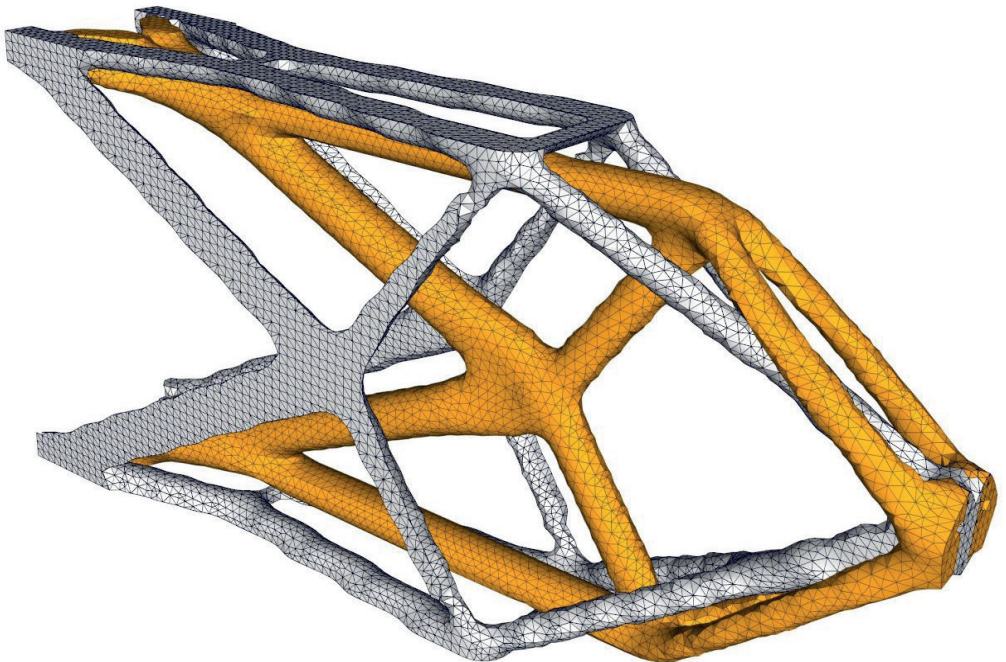


Topology optimization method for the adaptation of mechanical structures

Bergische Universität Wuppertal
Lehrstuhl für Optimierung mechanischer Strukturen

Saad Eddine Hafsa



Topology optimization method for the adaptation of mechanical structures

**Thesis
to obtain a doctoral degree**

in the
School of Mechanical and Safety Engineering
of the
University of Wuppertal



Submitted by
Saad Eddine Hafsa
from Tunis

Wuppertal 2020

Berichte aus dem Maschinenbau

Saad Eddine Hafsa

**Topology optimization method for the adaptation
of mechanical structures**

Shaker Verlag
Düren 2021

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Wuppertal, Univ., Diss., 2021

Copyright Shaker Verlag 2021

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-8306-4

ISSN 0945-0874

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

Saad Eddine Hafsa

Topology optimization method for the adaptation of mechanical structures

PhD thesis, University of Wuppertal, School of Mechanical Engineering and Safety Engineering, Chair for Optimization of Mechanical Structures, december 2020

Abstract

Adaptation of structures is done when an object is used commonly in a product family with variants having different requirement levels. An example of this process is when a series vehicle is the basis for the design of a motorsport vehicle where stiffness and rigidity behavior have to be adapted to a new specific use. To do so, reinforcements are added using specific struts and framework structures.

To find the topology of these reinforcing structures, the known topology optimization methods do not deliver satisfying results because the added material is spread on the surface of the basis structure, which makes their manufacturing difficult and costly.

In this thesis, an analysis of the adaptation task from the structural point of view is made and compared to the classical structural design and optimization task from scratch. All adaptation cases are classified depending on the type of basis structure and the investigated load case. Furthermore, some benchmark problem statements to assess the performance of adaptation methods are proposed.

A new method is presented that allows to generate reinforcing structures that are producible, without significant loss in performance compared to the results obtained with the so far available methods. In order to give the user more control over the optimization outcome, several features are implemented as input parameter such as the distance between basis and added structures or the properties of the connections between them.

To validate the method, an extensive parameter study applied on several adaptation cases and on 2D and 3D models is conducted. Finally some further adaptation cases are investigated, such as when members of the basis structure are removed and sequential steps adaptations.

Keywords: Topology optimization, adaptation, reinforcement, pre-existing members, density method, geometric features, framework structures, vehicle body.

Saad Eddine Hafsa

Topologieoptimierungsmethode für die Adaption von mechanischen Strukturen

Dissertation, Bergische Universität Wuppertal,
Fakultät für Maschinenbau und Sicherheitstechnik,
Lehrstuhl für Optimierung mechanischer Strukturen, Dezember 2020

Kurzfassung

Wenn eine Komponente kommunal innerhalb einer Produktfamilie verwendet wird, obwohl unterschiedliche Anforderungen an das Gesamtsystem vorliegen, wird eine Adaption der Strukturen benötigt. Ein Beispiel hierfür ist die Anpassung eines Serienfahrzeugs als Basis der Entwicklung eines Rennsportwagens bei dem Steifigkeiten und Festigkeiten für den neuen Anwendungszweck angepasst werden müssen. Zu diesem Zweck werden Verstärkungen in Form von Streben und Fachwerkstrukturen hinzugefügt.

Die bestehenden Optimierungsmethoden zur Ermittlung der Topologien der verstärkenden Strukturen liefern nicht umsetzbare Ergebnisse. Dies liegt daran, dass das hinzugefügte Material auf die Oberfläche der Basisstruktur verteilt wird. Hierdurch wird eine Interpretation und Herstellung schwierig und teuer.

In der vorliegenden Dissertation wird die Adaptionaufgabe aus Gesichtspunkten der Strukturauslegung untersucht und mit klassischen Strukturoptimierungsproblemen verglichen. Alle Adaptionfälle sind klassifiziert in Abhängigkeit von der Art der Basisstruktur und dem untersuchten Lastfall. Außerdem werden Benchmark-Modelle, um die Leistung von Adaptionmethoden zu prüfen, vorgeschlagen.

Eine neue Methode wird vorgestellt, die es ermöglicht herstellbare, verstärkende Strukturen zu generieren ohne Verlust an Steifigkeitspotenzial im Vergleich zu vorhandenen Methoden. Um den Anwender mehr Einfluss auf die generierten Topologien zu geben, werden mehrere Merkmale als Eingabeparameter implementiert. Hierzu zählen beispielsweise der Abstand zwischen Basis und verstärkenden Strukturen sowie die Eigenschaften der Verbindungselemente.

Um die Methode zu validieren, wird eine umfangreiche Parameteranalyse durchgeführt und in mehrere Adaptionfälle auf 2D und 3D Modelle angewendet. Abschließend werden weitere Adaption-Problemstellungen untersucht. Hierzu gehört der Fall, bei dem Teile der Basisstruktur entfernt werden. Ein weiteres Beispiel ist die Durchführung einer Adaption in sequentiellen Schritten.

Stichworte: Topologieoptimierung, Adaptation, Verstärkung, Basisstruktur, Dichtemethode, geometrische Eigenschaften, Fachwerkstrukturen, Karosserie.

Acknowledgments

This thesis was written during my employment as PhD Student at the BMW Group in the department for the design of motorsport vehicles. I would like to thank here everyone who contributed to the success of this project.

First of all I would like to thank my doctoral thesis supervisor Prof. Dr.-Ing. Axel Schumacher who gave me throughout the project the right advice to achieve advances in this research field and successfully find a solution to this topic. Also I address my thanks to all the actual and former PhD students of the chair who were a precious source of inspiration and improvement ideas.

To Prof. Dr. Wolfgang Achtziger from the Friedrich-Alexander University Erlangen-Nuremberg I would like to address my sincere gratitude for accepting to be the second reviewer for the assessment of this thesis.

My group leader at BMW Group Olivier Janssonie gave me the necessary space to focus on my thesis, by understanding the requirements of a research activity inside an industrial environment. He was also a great help by challenging me on the benefits of my results for practical applications.

My supervisor Mohammed Ruhaidi gave me all the necessary tools to conduct my research in the best conditions and gave me important insights in the structural computation challenges in motorsport environment.

I am grateful for the financial support from the BMW Group and for their ProMotion program through which I met several other PhD students in diverse research fields, which lead to interesting discussions and exchanges. Just to name a few I thank Dr.-Ing. Mariam Jaber and Dr.-Ing. Alaa Mourad for their continuous support.

A special thanks goes to Javed Butt and Jens Trilling who helped me through their internships and thesis works with great commitment and essential contributions for the success of this work.

The final thanks goes to my family and friends who supported me during this journey.

Wuppertal in december 2020

Saad Eddine Hafsia

Contents

List of Acronyms and Symbols	I
1 Introduction	1
1.1 Motivation and problem statement	1
1.2 Method and outline of the thesis	2
2 Fundamentals of structural design and optimization	5
2.1 Definitions	5
2.2 Design process and adaptation of structures	6
2.2.1 Design of mechanical systems	6
2.2.2 Adaptation of structures	7
2.3 Structural analysis	12
2.3.1 Pre-processing	12
2.3.2 Solving	13
2.3.3 Post-processing	14
2.3.4 Two dimensional bilinear quadrilateral square elements	14
2.3.5 Three dimensional hexahedron element	15
2.4 Structural optimization	17
2.4.1 Fundamental notions in structural optimization	17
2.4.2 Classification of structural optimization tasks	19
2.4.3 Mathematical background of optimization	20
2.4.4 Classification of optimization problems	22
2.4.5 Classification of optimization methods	23
2.5 Topology optimization with the density method	25
2.5.1 Problem formulation for minimum compliance design	25
2.5.2 Optimization method	26
2.5.3 Design parametrization and material interpolation	27
2.5.4 Sensitivity analysis	28
2.5.5 Filtering method	29
2.5.6 Optimality criteria method	30
2.6 Software for topology optimization	34
2.6.1 The 88 line code for two dimensional models	35
2.6.2 The 169 line code for three dimensional models	36
2.6.3 Import of external geometry as basis structure	37
2.6.4 Export of results for further processing	37

2.7	Benchmark problems in structural optimization	38
2.7.1	Problems for structures from scratch	39
2.7.2	Proposed problems for adaptation of structures	40
3	State of art methods on the adaptation of structures	45
3.1	Literature review	45
3.2	Adaptation results with the 88 line code	50
3.2.1	Method	50
3.2.2	Applications	51
3.3	Adaptation results with commercial software	59
3.3.1	Standard process	60
3.3.2	Additional constraint on the boundary zone elements	63
4	Developed methods for the adaptation of structures	65
4.1	Description of required results and features	65
4.2	Approaches to influence the results in the density method	66
4.3	Feature: minimum distance between basis and added structure	67
4.3.1	Approach to achieve a minimum distance	67
4.3.2	Data: extraction of element sets	69
4.4	Feature: geometry of connection zones	71
4.4.1	Minimum length scale of the connections	72
4.4.2	Circular / spherical geometry of the connections	74
4.4.3	Rectangular / cubic geometry of the connections	82
4.4.4	Specific shape of the connections	84
4.5	Feature: number of connections and distance between them	85
4.5.1	Splitting of large connections	86
4.5.2	Merging of proximal connection zone groups	91
4.6	Feature: removal of local reinforcements	93
4.7	Workflow	95
5	Two-dimensional applications and validation	99
5.1	Tensile beam	99
5.2	Cantilever beam	101
5.3	MBB beam	104
5.4	Michell cantilever	106
5.5	Arbitrary-basis-A	107
6	Three-dimensional applications and validation	111
6.1	Tensile beam	111
6.2	Cantilever beam	113

6.3	MBB beam	115
6.4	Michell cantilever	117
6.5	Arbitrary-basis-A	119
7	Influence of the parameters on the adaptation topologies	121
7.1	Penalization of boundary zone	121
7.1.1	Sensitivity penalization with factor	121
7.1.2	Sensitivity penalization with exponent	125
7.2	Continuation method for adaptation	127
7.2.1	Application on 2D examples	128
7.2.2	Application on 3D examples	130
7.3	Size of the boundary zone	131
7.3.1	Tensile beam 2D	131
7.3.2	Cantilever beam 2D	131
7.3.3	Arbitrary-basis-A-2D	132
7.3.4	Cantilever beam 3D	132
7.3.5	Michell cantilever 3D	133
7.3.6	Arbitrary-basis-A-3D	134
7.4	Influence of the volume fraction	134
7.4.1	Cantilever beam 2D	135
7.4.2	Arbitrary-basis-A-2D	136
7.4.3	Cantilever beam 3D	137
7.5	Mesh dependency	140
8	Optimization results for further adaptation cases	141
8.1	Slightly different loads	141
8.2	New load	149
8.3	With prior removal of a basis member	153
8.4	Extension of design space in depth	156
8.5	Sequential steps adaptation	157
9	Summary and Outlook	159
	References	162